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PhD Thesis

Value Chain Optimisation in Biogas Production

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September, 2017

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PREFACE

This thesis has been submitted to the Department of Management Engineering at the Technical University of Denmark (DTU), in partial fulfilment of the requirements for acquiring the PhD degree. The work has been supervised by Marie Münster and David Pisinger (DTU), and Ole Jørgen Hanssen (Ostfold Research, Norway).

The PhD study has been funded by the Danish Council of Strategic research as part of the interdisciplinary research project BioChain and was conducted from August 2013 to September 2017.

The thesis consists of two parts. The first part introduces the thesis background and motivation. It gives a brief overview of methods applied and a summary and discussion of the achieved results. The second part is a collection of the six research papers that has been written during the PhD study.

Ida Græsted Jensen

September, 2017

SUMMARY

With an increased focus on climate change and an increasing number of unpredictable and fluctuating renewable energy sources, a predictable renewable energy carrier is needed to stabilise energy production. Biogas can potentially be used for this but biogas projects struggle with becoming economically feasible.

In this PhD thesis, the focus is to create models for investigating the profitability of biogas projects by: 1) including the whole value chain in a mathematical model and considering mass and energy changes on the upstream part of the chain; and 2) including profit allocation in a value chain consisting of heterogeneous owners. To address the first point, a mathematical model based on network-flow optimisation has been developed to include the mass and energy losses in the chain. Furthermore, a method for simplifying the calculation of transportation costs has been included. Last, the costs on the biogas plant has been included in the model using economy of scale. For the second point, a mathematical model considering profit allocation was developed applying three allocation mechanisms. This mathematical model can be applied as a second step after the value chain optimisation.

After concentrating on how to make biogas economically feasible, the use of biogas in the energy system is considered by applying the energy systems model Balmorel and: 1) increasing the cost of CO_2 to reach a combined goal of biogas and biomethane; and 2) including the production of renewable gas and fuels in the energy systems model to find the optimal end use of each type of gas and fuel.

The main contributions of this thesis are the methods developed on plant level. Both the mathematical model for the value chain and the profit allocation model can be generalised and used in other industries where mass and value of the goods in the chain changes independently from each other and where several heterogeneous owners interact to make the value chain work. This could be other bioenergy projects as well as e.g. a value chain for clothing or cars.

Dansk sammenfatning

Med øget fokus på klimaændringer og en stigende mængde uforudsigelige og varierende vedvarende energikilder er der behov for en forudsigelig vedvarende energibærer for at stabilisere energiproduktionen. Biogas kan potentielt benyttes til dette, men biogasprojekter slås ofte med at være økonomisk rentable.

I denne ph.d.-afhandling er der fokus på at udvikle modeller for at undersøge den økonomiske rentabilitet af biogasprojekter ved at: 1) inkludere hele værdikæden i en matematisk model og tage hensyn til masse- og energiforandringer i den første del af kæden; og 2) inkludere profitallokering i en værdikæde bestående af heterogene ejere. Til det første punkt er en matematisk anlægsmodel baseret på network-flow optimering udviklet for at inkludere masse- og energitabet i kæden. Derudover er der udviklet en metode til forenkling af beregningen af transportomkostningerne. Endelig er stordriftsfordelene medtaget i modellen i form af omkostningerne på biogasanlægget. For at adressere det andet punkt blev en matematisk model til profitallokering udviklet ved brug af tre tildelingsmekanismer. Denne model kan anvendes efter brug af anlægsmodellen.

Efter at have været koncentreret om hvordan biogas kan gøres økonomisk rentabelt, adresseres anvendelsen af biogas i energisystemet ved at anvende energisystemmodellen Balmorel, hvor: 1) CO_2-omkostningerne varieres for at nå et kombineret mål for biogas og biometan; og 2) produktion af fornybare gasser og brændsler inkluderes i energisystemmodellen for at finde den optimale brug af hver type gas og brændsel.

De vigtigste bidrag fra denne afhandling er de metoder, der er udviklet på anlægsniveau. Både den matematiske model for værdikæden og profitallokeringsmodellen kan generaliseres og anvendes i andre industrier, hvor masse og værdi af varerne i kæden ændres uafhængigt af hinanden, og hvor flere heterogene ejere interagerer for at få værdikæden til at fungere. Dette kunne være andre bioenergiprojekter såvel som f.eks. en værdikæde til tøj eller biler.

Acknowledgement

This thesis is a product of a long journey from my starting point knowing close to nothing about biogas and the energy system. First, I want to thank the large group of supervisors who agreed to be part of the journey. I want to thank Marie Münster for leading me into the mystery world of energy systems and for seeing things from another perspective than my operations research perspective.

I want to thank David Pisinger for his enthusiasm, for his way of always providing relevant feedback in the most positive way, and for still wanting to be my supervisor after several supervisor-duties during my bachelor and master studies. I can truly say that you are the best supervisor from the field of operations research, I have ever had.

Ole Jørgen provided me with feedback, which was necessary in the last phase of the journey, and for this I owe him thanks. I want to thank Nina Juul, who was initially one of my supervisors, for being the connection between operations research and energy, which lead me safely through the first half of my studies.

I want to thank all of my colleagues from Systems Analysis for creating a nice working environment with just the amount of sweets that is needed to get through a tough day. A very special thanks goes to Lise Skovsgaard for fruitful article writing, for sharing good and bad parts of both the PhD and life outside, and for being a great moral support. Henrik Klinge Jacobsen, Hans Ravn, Amalia Rosa Pizarro Alonso, and Rasmus Bo Bramstoft Pedersen were all part of making this thesis happen with fruitful discussions of everything from technical details in biogas conversion to modelling in Balmorel and with article writing.

The project was never going to happen without the project partners of the BioChain project, so a big thank goes out to them. In particular, I want to thank Sven G. Sommer, SDU, for his role as project leader, Alessio Boldrin, DTU, and Jin Mi Triolo, SDU, for making the joint article happen, Lone Abildgaard, AgroTech, and Alan Lunde, Maabjerg Bioenergy, for providing me with data and for discussing the results of the models, and Kari-Anne Lyng, Ostfold

Research, for a good collaboration on article writing and at the project meetings.

I want to thank my family for being there for me. I want to thank Kim for believing in me, also during the times where I could only see a never-ending tunnel of darkness. I want to thank our two fantastic, funny, and stubborn girls, Thea and Gry, for not giving me a second of not being mum when I enter the door at home. Last, I want to thank my parents for their support even though their interest in—or at least their knowledge of—operations research is non-existent.

LIST OF PUBLICATIONS

Articles included in the thesis

Paper A: Alessio Boldrin, Khagendra Raj Baral, Temesgen Fitamo, Ali Heidarzadeh Vazifehkhoran, Ida Græsted Jensen, Ida Kjærgaard, Kari-Anne Lyng, Quan van Nguyen, Lise Skovsgaard Nielsen, and Jin Mi Triolo. "Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting". In: *Energy* 112 (Oct. 2016), pp. 606–617. DOI: 10.1016/j.energy.2016.06.068

Paper B: Ida Græsted Jensen, Kari-Anne Lyng, Marie Münster, and Ole Jørgen Hanssen. "Review of economic optimization models of supply chains in the bioenergy industry". *Submitted to Renewable and Sustainable Energy Reviews*. Aug. 2017

Paper C: Ida Græsted Jensen, Marie Münster, and David Pisinger. "Optimizing the supply chain of biomass and biogas for a single plant considering mass and energy losses". In: *European Journal of Operational Research* 262.2 (Oct. 2017), pp. 744–758. DOI: 10.1016/j.ejor.2017.03.071

Paper D: Lise Skovsgaard and Ida Græsted Jensen. "Why would biogas plants choose to upgrade?" *Submitted to Energy Economics*. June 2017

Paper E: Ida Græsted Jensen and Lise Skovsgaard. "The impact of CO2-costs on biogas usage". In: *Energy* 134 (Sept. 2017), pp. 289–300. DOI: 10.1016/j.energy.2017.06.019

Paper F: Rasmus Bramstoft, Amalia Pizarro Alonso, Ida Græsted Jensen, Marie Münster, and Hans Ravn. "Modelling of renewable gas and fuels in future integrated energy systems". *Working paper*. Sept. 2017

Articles not included in the thesis

Ida Græsted Jensen, Niels Framroze, Giovanni Pantuso, and Nina Juul. "Generating Scenario Trees for the Participation of Electric Vehicles in Electricity Markets". *Submitted to Energy*. Mar. 2017

Rasmus Bramstoft, Ida Græsted Jensen, Amalia Pizarro Alonso, Marie Münster, and Hans Ravn. "Modelling of Renewable Gas in the Future Energy System". In: *International Gas Union Research Conference*. 2017

Contents

Part I

Introduction and Theory

Chapter 1

Introduction

With an increased concern about global warming and its impact on e.g. sea levels and extreme weather, renewable energy has received a great focus for ensuring a shift from CO_2-emitting energy sources in the energy system. The Danish energy system includes a large share of renewable energy but still depends on fossil fuels, however, by 2050 all energy consuming sectors should be independent of fossil fuels [8]. With a large share of wind turbines having a great variability in production, an energy carrier with a predictable production pattern is needed. Biogas can be characterised as this and has the potential of providing a substantial contribution to the conversion of the Danish energy system.

Biogas is produced through anaerobic digestion of biomass, where biomass is converted into biogas and by-products. Biogas, a mixture of methane and carbon dioxide, can then be converted into other useful types of energy. In Denmark, biogas has traditionally been produced from a mix of manure and other substrates like dairy and slaughterhouse waste. Biogas is considered a renewable fuel as it is based on natural resources and waste products.

The use of manure in biogas plants makes the biogas potentially green house gas reducing, as climate gasses—including methane—from the raw manure would otherwise be emitted into the atmosphere when the manure is spread directly on the soil. The residue from the biogas production can be used as fertiliser on the fields, which according to Lukehurst et al. [22] potentially gives a better utilisation of the nutrients in the soil depending on biomasses in the mix. Treatment of manure in biogas plants is therefore a good way to reduce emissions from farming. Because of the potential of being green house gas reducing, a target of using 50% of the available manure in Denmark for bioenergy production in 2020 was set in the Green Growth agreement in 2009 [10].

There are three potential conversions of the produced biogas, namely into heat, electricity or biomethane. The latter is upgraded biogas and has the same characteristics as natural gas and can therefore be injected into the natural gas grid and converted into heat or electricity at a later stage or used for industry or transport. When biogas is upgraded, there is a potential for a more flexible use, since biomethane can be stored in the natural gas grid for later use, e.g. when the power production from wind is low. Then biogas can be used as a relatively cheap power reserve. Functioning as a power reserve is an important feature of a fuel operating in an energy system with a high share of wind power and thereby unpredictability.

When this PhD project began, the development of new biogas plants in Denmark had been in doldrums for some years, despite the reasons for biogas being present in the energy system as presented above. From 2000 to 2005, the biogas production in Denmark had increased with nearly 32% but from 2005 to 2010, the increase was only 13%, leaving the biogas production at approximately 4.3 PJ in 2010 [9]. Even though the biogas production in Denmark increased to 6.3 PJ in 2015 [9], the full Danish biogas potential of 48.6 PJ[1] in 2020 [13] is still a distant goal.

A central problem of biogas production is the high costs that makes biogas feasible only with a high level of support. The feed-in premium for electricity based on biogas in 2016 was 164.9 €/MWh, corresponding to more than five times the average day-ahead electricity price in Western Denmark [31]. This is in contrast to the performance of other renewables as e.g. wind power, where DONG Energy recently won two bids in Germany that will receive no subsidies [12].

The centralised biogas plants involves many owners that will only participate if they gain from participating. The biogas plants can use a number of input types and supply chain designs, therefore, they are lacking methods and models to ensure the optimal set-up and thereby increasing the profitability. This project seeks to contribute to an increase in biogas production in Denmark by providing a tool that can optimise the profitability of the biogas value chain by taking into account the resources used, the size and types of the processes in the chain, utilisation of storages, pricing between the owners in the chain, and usage of the end products. The best use of biogas in the energy system in the future is not clear, as the representation of biogas in the existing energy systems models, to our knowledge, is not including all the possibilities of functioning

[1]This estimate is only considering the energy directly from the biomasses and not the increase in production when using methanation

as a power reserve. By learning from the detailed considerations on plant level, this project is expected to contribute with recommendations on the optimal use of biogas in the energy system.

Based on the above mentioned observations, the following research questions is addressed in this thesis:

- How can we ensure economic feasibility in biogas value chains?
- How can the profit be allocated within the value chain to give all relevant owners an economic incentive to participate?
- What is the optimal use of biogas in the Danish energy system?

The research questions will be answered through the goals of this PhD project, which are to:

- Develop methods to overcome the challenges when modelling a value chain with heterogeneous owners
- Develop decision tools that can generate relevant information for investors, political decision making, and scientists
- Improve the modelling of biogas in existing energy system models

1.1 Thesis structure

Part I introduces the theory and concepts, and contains three chapters in addition to this chapter.

Part II contains each of the included papers. These are:

Paper A is a journal paper published in *Energy*. It introduces a method for evaluating both the energy and greenhouse gas balances and the economics of a biogas plant value chain, which is applied to a Danish case study using nine scenarios. For the paper, a method for simplifying the modelling of transportation costs was developed.

Paper B is a journal paper submitted to *Renewable and Sustainable Energy Reviews* and under the first round of review. It is a literature review of existing models for optimising the biogas value chain both for a single plant and on a regional level with several producers.

Paper C is a journal paper published in *European Journal of Operational Research*. In the paper, the model for optimising the value chain is introduced. The model handles mass and energy losses across the chain and includes economy of scale on the biogas plant.

Paper D is a journal paper submitted to *Energy Economics* and under the first round of review. It is drawing on the model from paper C and introduces three profit allocation mechanisms to evaluate the willingness of the owners to participate in the value chain and, based on the results, discusses why we see many biogas plants in Denmark that upgrade biogas to biomethane for grid injection.

Paper E is a journal paper published in *Energy*. In this paper, biogas and biomethane are included in an energy systems model. The use of these fuels in the energy system are discussed and analysed when the CO_2-cost changes.

Paper F is a working paper. Here the roles of renewable gas and fuel in the future energy system are investigated using an energy systems model, where production of the gasses has been included in the model.

The remainder of part I is structured as follows. In chapter 2, the biogas value chain is introduced, the energy system in Denmark is presented, and the modelling challenges will be discussed. Chapter 3 introduces the methods that has been applied in the thesis. A conclusion and discussion of the research questions are given in chapter 4, together with a section on contributions and recommendations related to the PhD goals, and a section on further research.

CHAPTER 2

BIOGAS: THE SOLUTION TO OUR PROBLEMS?

As discussed in chapter 1, Danish biogas production is only at a fraction of its potential. Value chain optimisation can help production reach its potential. In this chapter, the biogas value chain is introduced together with an overview of challenges that has been addressed during this PhD-project when modelling the biogas value chain and when considering the issue of ensuring profit for all owners. Hereafter, the possible use of biogas in the energy system is discussed together with an overview of the challenges and requirements when analysing biogas as an integrated part of the energy system. How all the challenges are handled is further discussed in chapter 3.

2.1 The biogas value chain

A value chain is a supply chain where value is generated within the chain [32]. The value can be economic or a change in the specifications of the involved goods, giving it more value for the whole chain. The biogas value chain gets the value from the substrates that are transported to the biogas plant and converted into biogas. The biogas can be sold for energy production and the digestate used as fertiliser.

The chain discussed in this thesis is shown in figure 2.1. Here all the involved processes are shown. The first process is the collection from the farmers. The farmers are of different types, e.g. livestock farmers and straw producers. The manure and other input types are separated in the figure, as it is only the livestock farmers that use the biogas plant as a treatment of their input and thereby require the digestate in return. The chain does not include the production of substrates but uses data on when input can be collected. The circles in the graph represent possible storages.

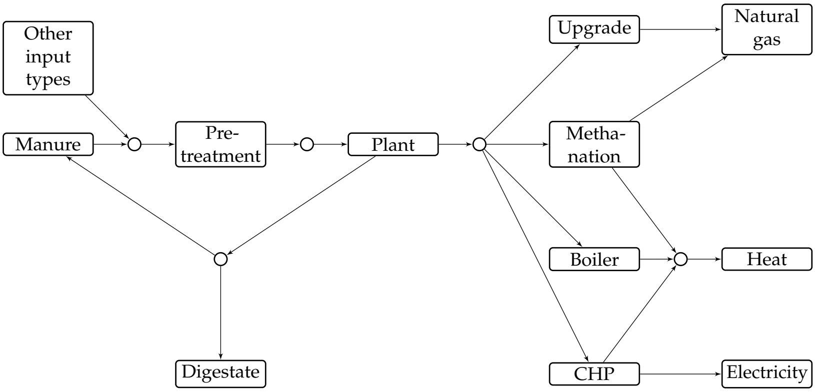

Figure 2.1: The biogas value chain from farmer to heat demand and energy markets.

The inputs are collected by the farmers, where a storage might be placed and some kind of pretreatment of the input might also be done at the farm. Transportation to the plant is carried out next. On the plant substrates are either delivered to a storage, a pretreatment facility, or directly put into the plant.

From the plant, several options for the produced biogas can be chosen. The produced biogas can from here take four directions: 1) be upgraded using methods where CO_2 is removed and the biogas is converted into biomethane, 2) be upgraded using methanation where H_2 is added to the biogas creating both biomethane and heat, 3) be burned in a heat boiler and thereby producing heat, or 4) be burned in a combined heat and power plant to produce both heat and power.

If one of the two first options are chosen, the biomethane, which has characteristics as natural gas, will be sold to the natural gas grid. The heat produced in option 2-4 can be sold to the local district heating system. The produced power from option 4 is sold to the electricity grid.

After the biogas production, there is a residue from the non-transformed inputs. This residue is called digestate and can be used as fertiliser. The digestate is usually sent back to the involved livestock farmers as they can use it on their land instead of the manure sent to the biogas plant. This involves some benefits for the farmers, as there are restrictions on how much nitrate can be spread on the field. Manure has a high level of nitrate and by mixing it with other inputs in the biogas plant, the nitrate level is often reduced. Farmers are therefore allowed to spread relatively more digestate on the fields than manure. Furthermore, the digestate is more accessible to the plants and hence less leaching, emissions to air, and odour problems occur. The digestate can also be sold elsewhere.

Modelling the full value chain

To find the optimal decisions for the structure of the value chain, an optimisation model can be used. In paper B, a literature review of existing optimisation models was performed. We found that the number of models focusing on plant level supply chains were much lower than the models focusing on regional supply chains. Only 15 out of the 61 models considered were plant level models. In order to answer the first two research questions regarding economic feasibility and profit allocation in the biogas value chain, the value chain model in this thesis has to be on plant level.

We investigated the elements included in the supply chains and, as shown in figure 2.2, we found that considerations on when to harvest/collect the inputs were considered in less than half of the plant level papers. Furthermore, pretreatment was considered in less than half of the papers, and storage after the anaerobic digestion was only considered in one paper. From this, we concluded that both the up- and downstream of the chain were only included in a few papers, see e.g. [20, 35, 36]. Of the models including both up- and downstream, only the model from [20] is a plant level model.

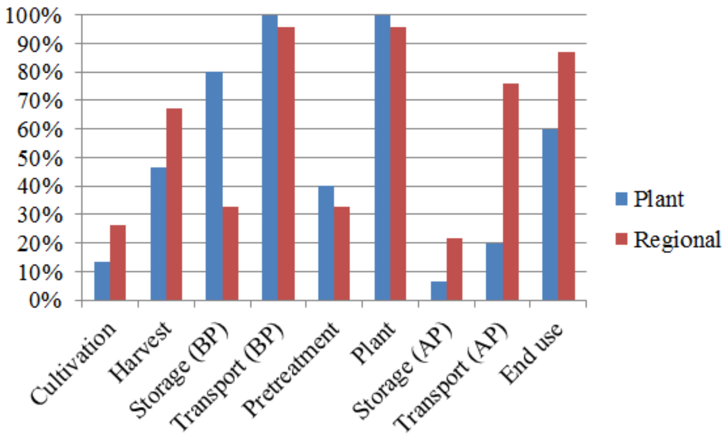

Figure 2.2: The supply chain elements included in the models shown as percentage of total amount of plant or regional models, from paper B

Based on this, we decided to analyse the biogas value chain stretching from the farmers to the heat demand and the power and gas markets. The inclusion of both sides of the chain is in our case relevant because of the heat demand as it is low enough to be a restricting factor for the optimal solution. Furthermore, there is no given price for biogas, so trying to solve the first part of the chain would either not give a surplus or force us to set a price for biogas, which is unknown. By setting a price for biogas, it becomes a restricting factor on the amount of biogas produced, and will therefore be a suboptimal solution to the problem. Finally, as discussed in paper B, the output side is necessary when the energy prices are fluctuating.

The time resolution of the models was also studied in the review. We found that few papers were using hourly or weekly resolution to capture fluctuations in energy prices and biomass availability. In figure 2.3 the time resolution used on the plant and regional models are presented. Here the absence of plant level models with a high time resolution is evident.

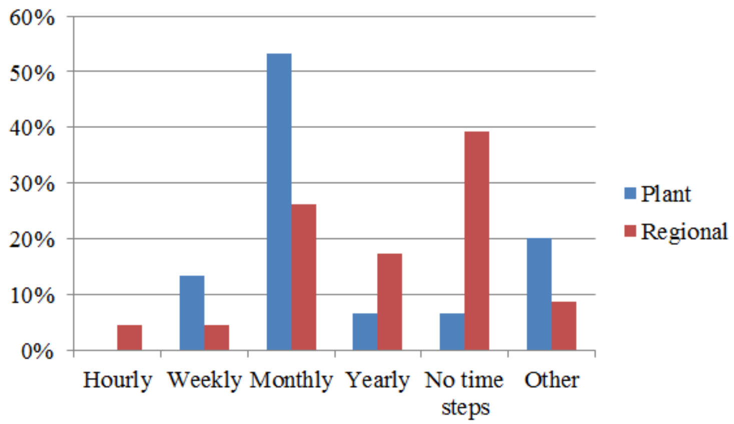

Figure 2.3: The time resolution for the models shown as the total amount of plant or regional models.

In order to capture seasonality of inputs as well as the fluctuations of energy prices, the model was designed such that the input side is in weekly time resolution and the output side is in hourly time resolution.

Modelling of the biogas value chain gives rise to some challenges. First, the input deteriorates over time. This means that there are mass and energy losses in the chain over time but potentially also increments in energy yield, as the energy is easier to extract from the biomasses. The mass and energy changes are not a challenge by itself, however, when the biogas content of the input changes over time and when it is not necessarily directly related to the mass loss, it becomes a problem when trying to model these changes, see section 3.1. The change in mass and energy content can happen anywhere in the chain but of the studied papers, none considered both types of changes. The problem is exemplified by the mass and energy yield changes for sugar beet during ensilage. The data obtained in the project shows that mass changes to 85% of the incoming mass when ensiling, but the energy yield increases with 2% as the energy is more accessible for the anaerobic process happening in the biogas plant.

Second, transportation costs of biomasses has a great influence on the total costs of the biogas project. In paper A, we found the transportation costs of biomasses in the range of 7-16% of total costs. Therefore, transportation plays a significant role in the optimal value chain, but transportation of biomass is a complex problem that could involve vehicle routing decisions as in [18], transportation mode choices [25], etc. To simplify the problem, a non-linear transportation cost function could be used, where transportation costs increase with the amount needed as the transportation costs are partly described by the distance driven. The result is a concave objective function and as we are maximising profit, this can be solved relatively easy, see section 3.2 and 3.3.

Third, economy of scale is present in most parts of the chain and complicates the modelling process. Economy of scale means that the cost of a process gets cheaper per unit the larger the process gets. This involves non-linear cost functions similarly to the transportation costs, however, in this case the result is a convex objective function, and thus gives a problem when solving, see section 3.3.

Profit allocation in the value chain

Many centralised plants are currently operating in Denmark [24]. All of these plants include a number of owners that must somehow agree on how to allocate the profit between them. A way of doing so is to use market prices between the owners. A challenge with this approach is to find the market price of the product that are traded as there are no established markets for most of these products. Alternatively, this can be considered as a profit allocation problem.

If the full value chain is profitable, it must be possible to allocate the profit between each owner such that all gain a profit. In the literature, profit allocation is mostly done in systems with homogeneous owners, see e.g. [15] where the sharing mechanisms Shapley value, nucleolus, and equal profit are applied to the problem of sharing cost between the participants in collaborative forest transportation, or [26] where the gain from cooperation between liquefied natural gas suppliers are allocated using nine methods ranging from equal repartition of the total gain to the disruption nucleolus. In the biogas value chain, the owners are heterogeneous, i.e. they do not provide the same service, so the same methods cannot always be applied. How to handle this is discussed in section 3.4.

2.2 Biogas in the energy system

As biogas includes many opportunities for usage in the energy system, it is relevant to consider the Danish energy system to evaluate the context in which the decisions of usage are taken. The Danish energy system consisted in 2015 of 56% renewable energy [9], and there is a need for constant development within this area to reach the targets of being fossil fuel independent in 2050 [8].

The current production of electricity and heat divided on input types are relevant to illustrate what biogas and biomethane are competing against, see figure 2.4.

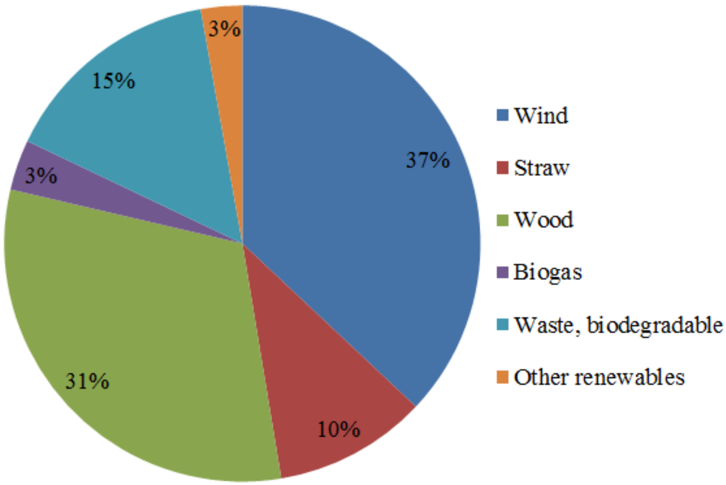

Figure 2.4: The renewable fuel usage of Danish heat and power production, 2015, [9]

For the power system, power must be provided to meet the demand at all times. With a high share of wind power this is a problem, as wind power is unpredictable and varies greatly both within a year but also within a day. Biogas can to some extent be used as a provider of flexibility when the wind power production varies.

In Denmark, the energy system is traditionally understood as the electricity and heating system. However, as biogas can be upgraded to natural gas quality, it is relevant to consider the natural gas grid as well when doing systems analysis for biogas. In the first half-year of 2016, the amount of biomethane (upgraded natural gas) injected into the natural gas grid corresponded to approximately 2.5% of the total gas consumption in Denmark. In the Danish Energy Agency's expectations for the expansion of biogas production, the biomethane in the gas grid will already in 2018 correspond to 5% of the total gas consumption in Denmark [14].

Analysing use of biogas in the energy system

Only few papers have focused on analysing the use of biogas in the energy system. In the papers by [5], [6], [7], [16], and [17], the future of bioenergy in the energy system is evaluated by means of energy systems models. In the papers [28], [29], and [30], treatment of waste is considered, and biogas is included only as a treatment of waste where the feedstock composition is fixed. As most of the biogas plants in Denmark are based on manure, the papers do not cover the situation of the biogas production.

As the literature shows, there is a need to further analyse the use of biogas in the energy system. To do so, it is necessary to handle both energy system specific and biogas specific challenges.

The demand of power and heat is time dependent and the demand must be satisfied in each time step. This means that the production of heat and power is also time dependent and one must ensure that the production is optimised for each hour. The time dependent production requires the analysis to have an hourly resolution.

To analyse the future energy system, it is necessary to take possible investments into account, as the existing capacities will come to an end due to their technical lifetime and the inclusion of biogas in the system might affect future investments.

Biomethane can be used as a substitute for natural gas. This must be taken into account when analysing the usage and costs, as biomethane can be utilised in existing natural gas plants, and the two fuels can be mixed to the like of the plant owner.

Last, it may be necessary to include the biogas production in the energy system as the biogas production is time dependent. The papers [16] and [17] are the only papers found to include bioenergy production in the optimisation. By including the biogas production in the energy system, several input types can be considered depending on the season and, furthermore, different end products can be chosen over the year.

CHAPTER 3

METHODS AND MODELS

As described in chapter 2, modelling of biogas with respect to the value chain and the energy system comes with some challenges. As described in section 2.1, the biogas value chain involves challenges with changes in both mass loss and biogas content over time, transportation of biomasses, economy of scale, and allocation of profit among the owners. In section 2.2, two challenges were described regarding the evaluation of biogas usage in the energy systems and the modelling of the production of biogas. Several methods have been applied to overcome the described challenges, and these methods are all introduced in the following sections. An overview of the included methods, the challenges they overcome, and in which papers they are applied is found in table 3.1.

3.1 Network-flow optimisation

Including both mass and energy losses in the chain is not straight-forward as the two types of losses must be handled separately, as described in section 2.1. To overcome this challenge, the value chain must be formulated such that both mass and energy content can be accounted for, and this can be done through a network-flow formulation of the value chain.

A general network-flow model includes a linear decision variable $x_{i,j}$ that decides the amount of flow between node i and j in the arc set $\mathcal{A}$. Let $c_{i,j}$ be the cost per unit of flow between i and j, then a general formulation of the

Method	Challenge	Paper A	Paper B	Paper C	Paper D	Paper E	Paper F
Network-flow optimisation	Mass and energy losses Storages			X	X		
Simplification of transportation costs	Transportation costs	X		X	X		
Modelling step-wise linear objective functions	Transportation costs Economy of scale			X	X		
Profit allocation	Findings incentives for participating				X		
Energy systems modelling	Investments Production Hourly resolution					X	X
Combining two technologies	Natural gas and biomethane					X	
Production of fuels	Including production of biofuels						X

Table 3.1: How the methods are used in the included papers

minimum cost network-flow problem, as given in [1], is:

$$\min \quad \sum_{(i,j)\in\mathcal{A}} c_{i,j}\, x_{i,j} \tag{3.1}$$

$$\text{S.t.} \quad \sum_{j|(i,j)\in\mathcal{A}} x_{i,j} - \sum_{k|(k,i)\in\mathcal{A}} x_{k,i} = b_i \qquad \forall i \in \mathcal{N} \tag{3.2}$$

$$l_{i,j} \leq x_{i,j} \leq u_{i,j} \qquad \forall (i,j) \in \mathcal{A} \tag{3.3}$$

In the mass balance constraint 3.2, the difference between the inflow and the outflow is determined by the parameter b_i. For the source node, b_i is greater than zero as there is only an outflow. For the sink node, b_i will be less than zero as it only has an inflow. For all other nodes, b_i is set to zero, meaning that what comes into the node must leave again. In constraint 3.3, a lower and upper bound of the flow can be given if necessary, if not the lower bound is set to zero and the upper bound is left out of the formulation.

The general formulation can be reformulated to a maximum flow problem, shortest path problem, etc. The network-flow formulation is useful for the biogas value chain and the challenges of energy and mass loss. For the challenge of mass loss, this can be included in the mass balance constraint 3.2, such that input amounts are multiplied with mass losses. When mass losses are included it is not possible to give a parametric value to the parameter b_i for the sink node as the amount will change depending on which way one travels through the network—and thereby which mass losses are implied. In these cases the parameter for the sink can be changed to be a variable instead. For the energy loss, the network—on which the model is built—can be formulated such that each node i includes the energy content at that node. This ensures that both energy losses and mass losses can be accounted for but are not directly related to each other.

Furthermore, the network-flow formulation makes it possible to include a detailed representation of storages. With this representation all input to the storage can be accounted for with respect to time in the storage but also the mass and energy losses during storage.

3.2 Simplification of transportation costs

The non-linear transportation cost function that was described in section 2.1, must be linearised. This can be done by dividing the cost function into smaller pieces and assuming a constant transportation cost per tonnes of biomass for each piece.

If the biomasses were distributed in one dimension, an approximation of the transportation distance for each piece could simply be the average of the breakpoints when assuming that the biomasses within each piece are spread out equally. The distance between a biogas plant and the j'th breakpoint is given by the variable r_j^{1D}, and the average distance, denoted by Δr_j^{1D}, is given by:

$$\Delta r_j^{1D} = \frac{r_j^{1D} + r_{j-1}^{1D}}{2}$$

The idea is now that the cost of transporting an amount that would require collecting biomasses both between 0–5 km and 5–10 km is the cost of collecting the amount located in the 0–5 km range with the average transportation distance for this piece, 2.5 km, plus the cost of collecting the amount located in the 5–10 km range using the 7.5 km average. This is a simplification that can only be applied in countries with a well-developed road network. Else, this distance measure is too far away from reality.

As the biomasses around a biogas plant are distributed in the plane, the above simplification must be translated to two dimensions. This can be done using concentric circles around the center as shown in figure 3.1 and assuming that the amount available in each circle is spread out equally in this circle. The average distance travelled in the plane, Δr_j^{2D}, must now be found using the area of the annulus, i.e. the area between two concentric circles. The average

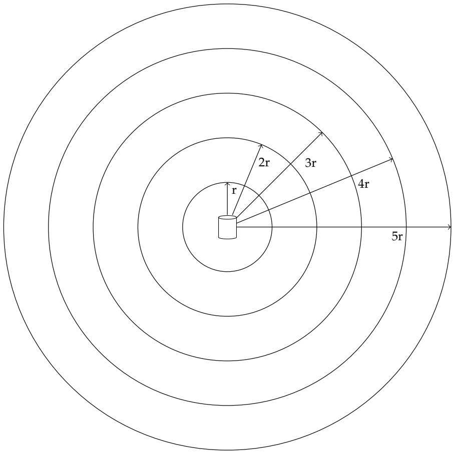

Figure 3.1: Concentric circles around the biogas plant used for simplifications of the transportation costs

distance can be found by using the average area of annulus j:

$$\Delta A_j = \frac{A_j + A_{j-1}}{2} \tag{3.4}$$

Using the formula for the area of a circle:

$$\pi\, \Delta(r_j^{2D})^2 = \frac{\pi\,(r_j^{2D})^2 + \pi\,(r_{j-1}^{2D})^2}{2} \tag{3.5}$$

Resulting in an average distance of:

$$\Delta r_j^{2D} = \sqrt{\frac{(r_j^{2D})^2 + (r_{j-1}^{2D})^2}{2}} \tag{3.6}$$

The transportation cost can now be calculated as for the one dimensional problem, using the distance for two dimensions. The result of this simplification is a step-wise linear convex function.

3.3 Modelling step-wise linear cost functions

Step-wise linear cost functions cannot directly be included in a linear programming model. When modelling the challenges of the biogas value chain as discussed in section 2.1, we encounter two types of step-wise linear cost functions, namely the transportation cost function and the cost function for economy of scale. When minimising the costs, the transportation cost function and the economy of scale cost function are of different types. The transportation cost function is, as described above, a convex function. Economy of scale is the situation where the per unit cost decreases with size, so it is a concave cost function. When modelling, these two types must be treated differently, and how to do so is presented below.

Convex functions

To include a step-wise linear, convex cost-function in the objective of a mathematical model, it is necessary to make use of convex combinations, which can be included as follows, see also [11]. The linearised and convex cost function is shown in figure 3.2. Here each line segment $s \in \mathcal{S}$ is shown with the parameter h_s denoting the width of the line segment s.

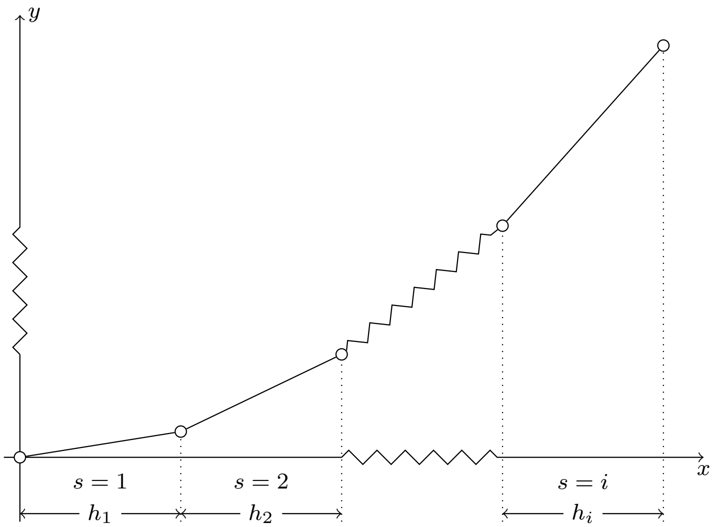

Figure 3.2: Optimisation of a convex function

The amount transported, x, is given by the variables, w_s, denoting how much of line segment s is taken up by the amount transported:

$$x = \sum_{s \in \mathcal{S}} w_s \tag{3.7}$$

Using convex combinations, the linearised cost function, $\varphi(x)$ can be modelled by:

$$\varphi(x) = \sum_{s \in \mathcal{S}} a_s \, w_s \tag{3.8}$$

Where a_s is a parameter giving the slope in line interval s. Now, the linearised cost function can be minimised by the following mathematical model:

$$\begin{aligned} &\min && \sum_{s \in \mathcal{S}} a_s \, w_s && && (3.9) \\ &\text{S.t.} && w_s \leq h_s && \forall s \in \mathcal{S} && (3.10) \\ & && w_s \geq 0 && \forall s \in \mathcal{S} && (3.11) \end{aligned}$$

It is worth noticing that the model works because the slope of each segment increases when x increases, so for any x, the w_s with the lowest index would be fully used first. The resulting problem is linear and can therefore be solved using a linear programming solver.

Concave functions

The concave economy of scale cost function can also be linearised, but as the function is concave and the first segments therefore are more expensive than the following, the model described in equations 3.9–3.11 would always utilise the last segments first for any given x-value. To model economy of scale, one needs to use an approach with breakpoints for a non-convex objective function [11], see figure 3.3.

Here the variables λ_k are decision variables for each breakpoint k on the cost function, where at most two can be non-zero. The two non-zero variables have to be consecutive and with $\hat{x}_k$ representing the x-value at breakpoint k, the optimal solution, x, can be represented by:

$$x = \sum_{k \in \mathcal{K}} \hat{x}_k \, \lambda_k \tag{3.12}$$

The cost of the solution is the linear combination of the decision variable and the cost function: $\sum_{k \in \mathcal{K}} f(\hat{x}_k)\lambda_k$, where $f(\hat{x}_k)$ is the value of the cost function in breakpoint k. Let δ_k be a binary variable equal to 1 if the optimal solution x is between $\hat{x}_k$ and $\hat{x}_{k+1}$. Now, minimising the cost can be modelled

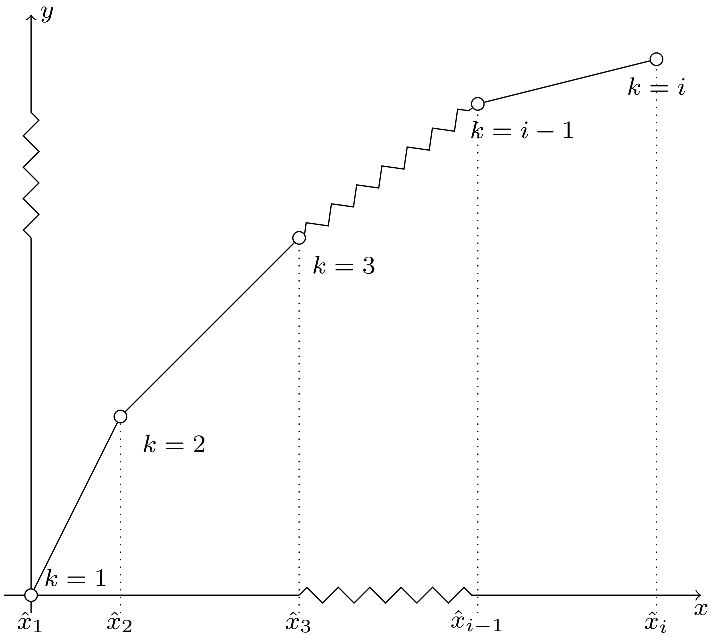

Figure 3.3: Optimisation of a concave function

as follows:

$$
\begin{aligned}
\min \quad & \sum_{k \in \mathcal{K}} f(\hat{x}_k)\lambda_k && && (3.13)\\
\text{S.t.} \quad & \sum_{k \in \mathcal{K}} \lambda_k = 1 && && (3.14)\\
& \lambda_1 \leq \delta_1 && && (3.15)\\
& \lambda_k \leq \delta_{k-1} + \delta_k && \forall k \in \mathcal{K} \setminus \{1, |K|\} && (3.16)\\
& \lambda_{|K|} \leq \delta_{|K|-1} && && (3.17)\\
& \sum_{k \in \mathcal{K}} \delta_k = 1 && && (3.18)\\
& \lambda_k \geq 0 && \forall k \in \mathcal{K} && (3.19)\\
& y_k \in \{0, 1\} && \forall k \in \mathcal{K} && (3.20)
\end{aligned}
$$

The objective function represents exactly the costs of the process. Equation 3.14 ensures that no λ_k is set to more than 1, while equation 3.15–3.17 ensures that λ_k are only non-zero if x lies between $\hat{x}_k$ and $\hat{x}_{k+1}$. Equation 3.18 ensures that at most one δ_k is set to 1.

The λ_k variables have the same characteristics as SOS2-variables that are variables where at most two variables can be non-zero and these two variables need to be consecutive. The concept of SOS2-variables are introduced by Beale and Tomlin [3], where a simplified version of the above model is given by:

$$\min \quad \sum_{k \in \mathcal{K}} f(\hat{x}_k)\lambda_k \tag{3.21}$$

$$\text{S.t.} \quad \sum_{k \in \mathcal{K}} \lambda_k = 1 \tag{3.22}$$

$$\lambda_k \text{ is an SOS2-variable} \qquad \forall k \in \mathcal{K} \tag{3.23}$$

Because SOS2-variables are implemented effectively in solvers like CPLEX, it was chosen to use the latter formulation for modelling economy of scale in the biogas value chain. However, economy of scale is a challenge when solving a large problem like the plant level problem, as it involves these SOS2-variables. This means that it should only be included if there is a strong need for it and data are available.

3.4 Profit allocation

When allocating profit among owners, the first thing to ensure is that all owners gain a profit. This is ensured by applying an allocation mechanism, which can be modelled with the following general model:

$$\max \quad z = \varepsilon \tag{3.24}$$

$$\text{S.t.} \quad \textbf{Feasibility constraint} \qquad \forall o \in \mathcal{O}^{feas} \tag{3.25}$$

$$\pi_o^{PA} = \gamma^{feas} C_o^* \qquad \forall o \in \mathcal{O}^{sub} \tag{3.26}$$

$$\pi_o^{PA} = \pi_o^* - \sum_{\substack{o' \in \mathcal{O} \\ |x^*_{o',o} > 0}} \rho_{o',o}^{PA} + \sum_{\substack{o' \in \mathcal{O} \\ |x^*_{o,o'} > 0}} \rho_{o,o'}^{PA} \qquad \forall o \in \mathcal{O} \tag{3.27}$$

$$\varepsilon \geq 0 \tag{3.28}$$

$$\pi_o^{PA} \geq 0 \qquad \forall o \in \mathcal{O} \tag{3.29}$$

$$\rho_{o,o'}^{PA} \geq 0 \qquad \forall o \in \mathcal{O}, o' \in \mathcal{O} \tag{3.30}$$

The objective function 3.24 is to maximise the variable ε, which again is given for each feasibility constraint tested. What ε represents, depends on the allocation mechanism applied. Constraint 3.25 is the relevant feasibility constraint for the allocation mechanism applied and is given in constraints 3.31–3.33 below. In the above model, it is assumed that a subset of the involved owners in the chain, as represented by the set $\mathcal{O}^{sub} \subset \mathcal{O}$, will need a fixed percentage, γ^{feas}, of their costs, C_o^*, covered. This results in the profit allocation given by variable π_o^{PA}, and is given by constraint 3.26. Last, the actual allocation of the profit between owners is done in constraint 3.27, where a price, $\rho_{o,o'}^{PA}$, is set between the owners in order to ensure the desired allocation.

To ensure an attractive value chain, the specific type of allocation mechanism must be considered and are represented by the feasibility constraint. Three types of feasibility constraints have been applied:

- Full equality, where all owners receive an equal share of the total profit:

$$\pi_o^{PA} = \frac{1}{|\mathcal{O}^{feas}|} \sum_{o' \in \mathcal{O}^{feas}} \pi_{o'}^{PA} \quad \forall o \in \mathcal{O}^{feas} \tag{3.31}$$

  Here ε is not included in the constraint, so to avoid an unbounded problem, ε is set to zero.

- Proportionality, where all owners get the same share, ε, of the costs, C_o^* covered:

$$\pi_o^{PA} = \varepsilon C_o^* \quad \forall o \in \mathcal{O}^{feas} \tag{3.32}$$

- Individual rationality, where the minimum distance, ε, from the allocated profit, π_o^{PA}, to the alternative profit, π_o^{ALT}, is maximised:

$$\pi_o^{PA} - \pi_o^{ALT} \geq \varepsilon \quad \forall o \in \mathcal{O}^{feas} \tag{3.33}$$

The two first allocation mechanisms are well-known within profit allocation theory, see e.g. [37] and [19], and when sharing with friends and family. The individual rationality mechanism was inspired by the so-called Nucleolus mechanism, where one seek to maximise the minimum distance between the allocated profit and the alternative profit for all subsets of the chain, see [4], as given by the constraint:

$$\sum_{o \in \mathcal{S}} \pi_o^{PA} - \sum_{o \in \mathcal{S}} \pi_o^{ALT} \geq \varepsilon \quad \forall \mathcal{S} \subset \mathcal{O}^{feas}, \mathcal{S} \neq \emptyset \tag{3.34}$$

The restriction with this allocation mechanism is, however, that the chain should be functioning using each subset of $\mathcal{O}^{feas}$. For the biogas value chain it makes no sense to remove one owner from the chain, as the owner would have to be replaced by another in this case. Therefore the individual rationality mechanism was designed to maximise each owner's profit of staying in the chain compared to the best alternative.

3.5 Energy systems modelling

Energy systems analysis focus on quantitative methods for evaluating the energy system. One method applied is energy systems modelling, where a mathematical model of the energy system is used to find the optimal structure of the energy system. In order to evaluate the use of biogas in the energy system, a mathematical model for doing so must be chosen, which fulfils the requirements: time dependent production, demand satisfaction, and investment decisions as described in section 2.2. Several energy systems models exist that can handle various aspects of energy systems analysis. These models ranges from e.g. the operational model EnergyPLAN [23], over the investment and operational models TIMES [21] and Balmorel [34], to the stochastic operational model Wilmar [27].

The Balmorel model is well suited for analysing biogas in the energy system, as it can optimise the system on an hourly level, includes investments if needed, and gives the user a possibility to include and—if necessary—develop new optimisation add-ons. As we are analysing biogas in the Danish setting, another relevant factor is that Balmorel already has a detailed representation of Denmark and the Nordic countries and that DTU has a large data set with technology data, costs etc.

Balmorel is an economic dispatch model where capacity investments can be included. A general formulation of the economic dispatch model with capacity investments is given below, see also [2]:

$$\begin{aligned}
\min \quad & z = \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} a_i p_{i,t} + \sum_{i \in \mathcal{I}} b_i p_i^{max} && && (3.35) \\
\text{S.t.} \quad & p_{i,t} \leq p_i^{max} && \forall i \in \mathcal{I}, t \in \mathcal{T} && (3.36) \\
& \sum_{i \in \mathcal{I}} p_{i,t} = d_t && \forall t \in \mathcal{T} && (3.37) \\
& p_{i,t} \geq 0 && \forall i \in \mathcal{I}, t \in \mathcal{T} && (3.38) \\
& p_i^{max} \geq 0 && \forall i \in \mathcal{I} && (3.39)
\end{aligned}$$

The objective function 3.35 is represented by two terms. The first represents the cost of production and the second the investment costs. Constraint 3.36 ensures that the installed capacity, p_i^{max}, is not exceeded by the production in each time period on that technology, $p_{i,t}$. Constraint 3.37 ensures that demand, d_t, is satisfied in all time periods.

Combination of two technologies

Besides being an economic dispatch model, Balmorel can be extended with so-called add-ons. Balmorel has a number of technologies to choose from when optimising the production, where each technology is specified by type of fuel, investment costs, production costs etc. To handle the case where biomethane and natural gas can be used by the same technology, two technologies must be combined to find the total capacity and production pattern.

Biomethane and natural gas can be used in either power-only units or heat-and-power units. For power-only units, the total capacity is given by the production using the biomethane and the natural gas. This can in general be formulated by:

$$p_{i,t} + \sum_{j \in \mathcal{J}(i)} p_{j,t} \leq c_i \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \tag{3.40}$$

Where the set $\mathcal{J}(i)$ contains the possible technologies that can be combined with technology $i \in \mathcal{I}$. In the case of biomethane and natural gas, i would be natural gas and j biomethane.

The heat-and-power units can be one of two types: back-pressure and extraction units. A back-pressure unit is the easiest type to handle as the ratio between heat and power is fixed. This means that the capacity when producing with two fuel types can be handled as in equation 3.40. An extraction unit has a variable ratio between heat and power so this must be handled differently using a C^v-coefficient representing the loss of electricity per unit of heat production as in the following:

$$p_{i,t} + \sum_{j \in \mathcal{J}(i)} p_{j,t} \leq c_i - C_i^v q_{i,t} - \sum_{j \in \mathcal{J}(i)} C_j^v q_{j,t} \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \tag{3.41}$$

Here the variable $q_{i,t}$ is the heat production of technology i in time period t.

These two extra constraints are handled in Balmorel by the CombTech add-on, which can also be used for more complicated combinations, e.g. a variation of the power-to-heat-ratio or different operational cost, than in the case of biomethane and natural gas.

Production of gas and fuels

Another relevant add-on to include in the Balmorel model is one that can handle production of gas and fuels. Traditionally, Balmorel has been applied for energy conversion into electricity and heat, but with a need for looking into the gas grid, it must be extended to include consideration of renewable gas and fuel production.

As described in section 3.1, network-flow optimisation is a good way to consider biogas production. Biogas production does not differ from other renewable gas production methods on the input side, i.e. biomass still has to be collected and transported, so these can be modelled in the same way.

This is handled by the add-on OptiFlow [33], which is a generalisation of the waste model OptiWaste. OptiFlow is a network-flow model that can model any network-flow related problem. As network-flow optimisation models are already described in section 3.1, no more details on OptiFlow is given here.

CHAPTER 4

CONCLUSION

In this chapter, each of the three research questions, as presented in chapter 1 are answered by presenting the work done during the PhD-study. Each of the papers are presented, hereunder the methods applied in each paper together with the result of each paper. Each section contains a discussion of the results, the methods used, and the replicability of the study in other countries.

Then, the thesis contributions and recommendations are discussed based on the PhD goals. Last, areas for further research are presented.

4.1 Ensuring economic feasibility in biogas value chains

Several steps had to be taken to answer the first research question:

How can we ensure economic feasibility in biogas value chains?

The first step was to make a simple spreadsheet model to find the economically best solution picking from nine scenarios. A wide search for input data for the economic data was performed and the method for quantifying the transportation costs was developed, see section 3.2. The model is documented in paper A, where also the energy and greenhouse gasses are accounted for to see if it is possible to find the best solution considering all three categories. The three individual models were tested on nine scenarios using pig manure and sugar beet as input in three ratios: 1:0, 7:1, and 3:1, with three sizes: 110,000, 320,000, and 500,000 tonnes input per year.

Results showed that using sugar beet is not a viable solution for a biogas plant given the assumptions on timing of pretreatment, input costs etc. This result indicates that an optimisation model might enhance the chance of finding profitable solutions for the chain. Before starting to implement an optimisation model, a literature study was performed to look into the different aspects that the model should cover. The literature review, see paper B, showed that only few models include both mass and energy losses, the value chain from farmer to energy demand, as well as storages.

In paper C, we presented the optimisation model covering the challenges of mass and energy losses, simplifaction of transportation costs, and economy of scale, as discussed in section 2.1. The model is from now on referred to as the plant level model. Network-flow optimisation was applied in order to formulate the model. The developed transportation method was included and modelled as described in section 3.3 and economy of scale for the investment and operational costs of the biogas plant was included as described in section 3.3. 2015 was used as modelling year and sensitivity analysis were performed on natural gas prices, electricity prices, heat demand, and subsidy for biomethane. Possible inputs were manure, sugar beet and straw. Results showed that the model can be used to find feasible solutions for the biogas value chain and thereby it can help with ensuring the economic feasibility in biogas value chains. The results also showed that methanation was the preferred energy converter, while the optimal input was a combination of manure and straw, and storages was used for the straw before feeding it to the biogas plants continuously over the year.

The plant level model comes with some limitations, where the biggest limitation is the input data. As the production costs of biogas are kept confidential by most plants, the input data with regard to production costs are highly uncertain. This is also true for the potential biogas yield of the biomasses and what happens with mass and energy content during pretreatment and storage. However, best available data were utilised for the analysis and as better data becomes available, e.g. from other partners in the BioChain-project, this can easily be incorporated in the current dataset.

Another limitation is the one year time horizon. As energy prices are fluctuating, the optimal solution one year might not be the optimal solution the next year. As biogas plants are supposed to have a relatively long lifetime of minimum 20 years, this will have an impact on the potential profits obtained. To overcome this challenge, one could optimise using different datasets for potential future energy prices and test the investment decisions for each instance in all other instances. Another way to overcome this issue is to include more years in the simulation. This would, however, increase the running time of the model significantly, which would possibly require the development of an algorithm for solving it.

For the economy of scale, it was decided only to include economy of scale on the biogas plant. In the upstream part of the biogas value chain, data on economy of scale were only available for the biogas plant so no other options were considered. On the downstream part of the chain, it was decided not to include economy of scale even though data were available. The inclusion of economy of scale would make the model slower, and as this would not represent the most important part of the costs and to avoid a too slow model, we decided not to include economy of scale on the downstream part of the chain. The inclusion of economy of scale in all processes is therefore possible future work for a better representation of reality.

The plant level model can be applied in a number of ways as it is quite flexible. First, it will be possible to change the data such that the model can be used in other areas in Denmark as well as other areas around the world. Also more input types can be added to the model so local resources can be included. Second, the model can be used for evaluating support and tax schemes. By changing the data on the support, one could give recommendations with regard to future ideas for support and their impact on the biogas plant and the willingness to produce either biogas or biomethane. Third, analyses could be performed to evaluate a biomass input's performance and at what price it could be used in the biogas plant.

4.2 Profit allocation in the value chain

A natural question when a value chain set-up has been decided is the second research question:

How can the profit be allocated within the value chain to give all relevant owners an economic incentive to participate?

This question was addressed in paper D where the idea was to include the owners in the biogas value chain and consider what happens when different allocation mechanisms are applied. A few changes were made to the plant level model from paper C to include the farmers in the chain. After running the plant level model, the three models for allocating the profit, as described in section 3.4, were applied.

Based on the results from the runs of the allocation, it was possible to study how the owners are affected by each allocation mechanism, and what the allocation could do for the owner's willingness to engage in the collaboration. Our results show that the three allocation mechanisms are allocating the profit quite differently, and the preferred allocation is different from plant owner to livestock farmer. However, the profit for each owner is fairly high for all three allocation mechanisms, so none of them should—as far as profit goes—scare any possible owner off. In figure 4.1, the spread in profit considering each of the allocation mechanisms is shown for the three owners we considered as necessary owners for a functioning value chain. The result shows that with a profit as significant as we find with the plant level model from paper C, it will be possible to find an allocation mechanism of the three mechanisms applied that gives an economic incentive to participate for all owners.

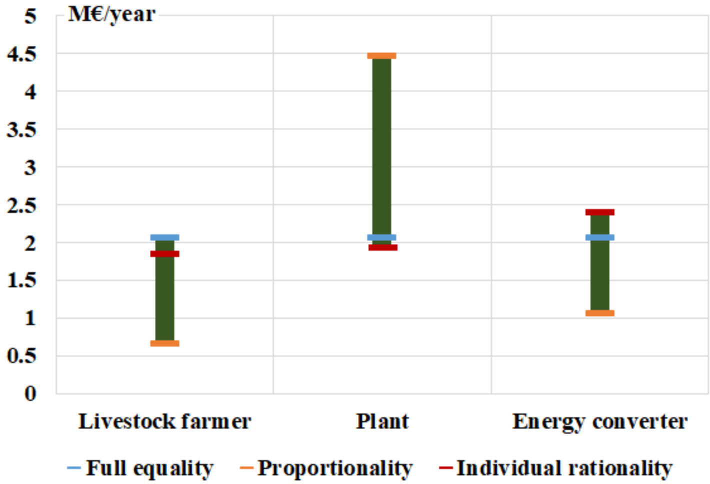

Figure 4.1: The spread of the profit for each of the necessary owners considering the three allocation mechanisms

Last, we considered the risk of a specific value chain configuration. Considering the risk and the prognosis of natural gas prices, we find that the best option for the value chain is to upgrade the biogas, which will still ensure an economic incentive for all owners. As the biogas plants being built in Denmark at the moment are all choosing to upgrade the biogas, we find that this result is in line with reality.

As for the plant level model from paper C, the limited data availability—particularly on operation costs—sets a limit to what results we can obtain, but the allocation model as described in 3.4 could be run without running the plant level model first to limit the need for data collection. This would restrict the necessary data to that of the owners, who would then need to report expected cost and income. This could make the owners exaggerate the costs such that more profit would be allocated to them. If this problem—referred to as adverse selection in economics—should be dealt with, an allocation mechanism for handling it should be developed, see e.g. [38].

Our set-up with first running the plant level model and then the allocation mechanism could—if necessary—be done differently. If the resulting allocation did not ensure participation of all owners, one could run the plant level model again with an extra constraint stating that for the stakeholder to be involved, the profit should at least be a certain amount for this owner. This would require including the price-variable between the owners in the plant level model, which would slow down the calculation time.

The model can—as the plant level model—easily be applied to other regions and countries by changing the data input, and the type of bioenergy can also be changed. With regard to the owners in the value chain it is possible to change which owners are present and which processes the owners possess, which would make the allocation model transferable to other bioenergy projects.

4.3 Usage of biogas in the energy system

After addressing the use of biogas from a private owner's perspective, it makes sense to consider the usage of biogas in the energy system and whether the current regulation on biogas results in the usage that is needed in the energy system. In the papers E and F, the last research question was addressed:

What is the optimal use of biogas in the Danish energy system?

In paper E, a first attempt to answer this question was made. The paper addresses how CO_2-costs affects the usage of biogas in the energy system. We used the Balmorel model with the combination of technologies add-on, CombTech, as described in section 3.5. Before applying CombTech, the add-on had to be revised as it was not functioning properly. By using the plant level model from paper C, a cost of biogas and biomethane produced by water scrubbing was found. A constraint for a combined target of biomethane and biogas was included in Balmorel and set to resemble the expected use in 2025. The expected CO_2-emissions of all fuels was included in the objective function as part of the operational expenditures. We tested the model using five damage cost estimates for CO_2-emissions to see the effect on the biogas usage from a socio economic point of view.

Our results showed that the biogas target for 2025 could only be reached when the CO_2-costs were very high. The paper does not include production of the biogas or the boost of output energy by methanation where heat is also produced. This will, however, affect the price of the biomethane and if the possibilities of switching between different production methods were included in the model, the flexibility of the biogas could be explored. Furthermore, the possible usage of other renewable gasses was not included. To consider these issues, biogas must be held up against the other renewable gasses and include production of fuels for transport as is done in paper F.

In paper F, production of renewable gas and fuels was included in the modelling and it was decided through the model whether the products should be delivered to the energy system or consumed as transport fuels. Balmorel was applied together with the add-on OptiFlow to find the optimal usage of bioenergy in the energy system in 2050. Before applying the OptiFlow add-on, we had to update data to reflect that of renewable gas and fuel production. We used a base case with possibility of investments in transmission lines, a high CO_2-cost, a normal gas price, and a biofuel demand of 50 PJ. One by one we varied these settings to show the effect of no investments in transmission line capacity, no CO_2-cost, a high gas price, and a biofuel demand either increasing or decreasing. When the biofuel demand is high, part of this is a demand for biojet fuels. Biogas production has been included in the modelling with the possibility of choosing a mixture of straw and wet biomasses or only the wet biomasses as the input to the biogas plant.

Our results showed that wind and solar power is used for providing the electricity needed in the energy system, and the heat is covered by heat generation from waste, heat pumps, and excess heat from the bioenergy production, however, biomethane is used for heat generation when the transmission investments are not included. Methanol is produced in all scenarios to supply the transport fuel demand, but biodiesel is produced as a by-product for biojet in the scenario with a specific demand for biojet, and therefore supplies some of the transport fuel demand in this case.

Biogas is produced and injected into the gas grid in all scenarios but the scenario where the CO_2-cost is set to zero. The injection to the gas grid happens as the biogas plants are located close to the resources, i.e. close to the livestock farmers in the decentral areas. When the natural gas price is high, the biogas is upgraded to natural gas quality using methanation else it is upgraded by water scrubbing. The results show that the inclusion of the possibility to choose a mix is needed, as biogas is produced mixing straw and wet biomasses in areas where straw is available, or by only including wet biomasses when straw is not available.

In both of the papers and for energy systems analysis in general, the uncertainty of input data is a problem for the interpretation of the results. Both of the methods for evaluating the system can though be applied using data for any desired country in question and proper sensitivity analysis carried out to handle the most obvious uncertainties. The latter method with using OptiFlow does, however, have a greater need of data to model the transportation costs as good as possible.

4.4 Contributions and recommendation of the PhD study

During the studies, it was possible to fulfil both of the PhD-goals. The first research goal was to:

Develop methods to overcome the challenges when modelling a value chain with heterogeneous owners

The first challenge identified was the challenge of a combined mass and energy loss of biomasses before using it as input to the biogas plant. It was found that network-flow optimisation can be used to model the two types of losses independently by letting the energy loss be represented by an extra index in the nodes. The method can be used in other value chains where the value of the goods in the chain changes independently of the mass, it must be accounted for separately as described above.

Another challenge was to simplify transportation costs to avoid a long running time. This can be done when the model of the value chain is not on an operational level. For this, the transportation method was developed to capture the dis-economy of scale when transporting biomasses. The method can be used to simplify transportation costs in all cases where transportation to a central point is modelled and the transportation costs are a significant part of the total costs but due to complexity or data availability must be simplified.

Last, the challenge with price setting between the owners was considered. The method developed can be used for profit allocation and thereby price setting between heterogeneous owners in other value chains, which to our knowledge has not been considered elsewhere.

Based on the methods developed, other modellers of value chains are advised to:

- Capture the change of mass and value using network-flow optimisation
- Consider the method for simplification of transport costs to avoid unnecessary running time
- Include profit allocation models to give all owners an economic incentive to participate

The second research goal was to:

Develop decision tools that can generate relevant information for investors, political decision making, and scientists

Several types of decision tools were developed for investors: the mathematical model from paper C, considering the allocation of profit in paper D, and considering both economic and environmental effects in paper A. Based on these papers, the following recommendations for investors can be made:

- Include considerations of value chain processes to optimise the input and output from the biogas plant
- It is possible to make profit allocations that will satisfy all owners but the allocation mechanisms should be transparent and agreed upon beforehand

A political decision will affect the configuration of the value chain, and how much can be evaluated by applying regulation changes to the model from paper C. The political decision makers are therefore recommended to:

- Consider the effects of regulation changes in the plant level model to evaluate if the changes have the desired effect

The literature review from paper B showed that there were some gaps in the literature to fill. With the model from paper C, we included the full value chain and by showing that this was possible, we contributed to the knowledge base. Recommendations for other modellers of biomass value chain are to:

- Model the chain from the farmer to the energy markets
- Consider the necessity of modelling each process explicitly to avoid unnecessary running time

The last research goal was to:

Improve the modelling of biogas in existing energy system models

By including the production of biogas in Balmorel as in paper F, we showed how the modelling could be improved. The inclusion of production increases the exactness of the model, as all related costs can be treated with the inclusion. Therefore, it is recommended to consider production in future evaluations of bioenergy in the energy system.

For political decision makers, it is relevant to consider both the plant level model and the energy systems model. The two models can interact as a change in regulation will result in other biogas and biomethane prices and this will give another optimal use of biogas. The political decision makers are therefore recommended to:

- Learn from the energy systems model with regard to finding the value of supporting biogas, but apply new regulation in a plant level model to see how the biogas value chain will respond to the changes

4.5 Future work

During the last phase of the PhD studies, several ways to improve the model from paper C for a better representation of reality were considered. First, the economy of scale inclusion of the plant could be extended to cover all the processes where data are available. Given the collected data, it would have been possible to include it on the desulfurisation technologies, some of the CHP units, and most of the upgrading processes.

Another issue has been the uncertainties of energy prices. As the results showed in paper D, there is a significant difference in the optimal supply chain from year to year depending on the combination of heat price, electricity price, and natural gas price. In order to decide on the optimal supply chain configuration, the time horizon could be extended to take the development in energy prices into account, or a stochastic programming model could be used to consider the possible scenarios in the future.

The main problem with the possible extensions are running time. Given the current set-up, the running time is between 10 minutes and 1 hour depending on the input data. A necessary consideration is therefore to find a way to reformulate the model in order to solve the model faster. One possible way could be to use column generation where each column represents a possible way through the network and requires a revision of the way the model is written. Another way to handle the running time is to develop a metaheuristic to solve the problem.

The original idea was to include the decision of ownership of each process to the profit allocation model to see how it influences the willingness to participate in the biogas project. This would be interesting to explore and could possibly be achieved by setting up ownership structure scenarios that could then be run in the profit allocation model. Furthermore, it could be interesting to extend the profit allocation model to consider the cases where a profit allocation does not give all owners an economic incentive to participate. In this case, the model from paper C and the profit allocation model could be connected in a loop where additional constraints are added to the first model, if the profit allocation is not successful.

Finally, some enhancements could be done for the energy systems model and specifically on the OptiFlow add-on. It would be relatively easy to implement the transportation method as described in section 3.2 and 3.3. This inclusion does, however, mean that detailed data on biomass location must be available in the country of the study. It will also require a closer look at the geographic representation in Balmorel, as the areas used in the current version of the model are largely aggregated and therefore cannot be placed directly on a map.

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Part II

Papers A-F

Paper A

Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting

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Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting

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A B S T R A C T

Several countries have established a number of increased targets for energy production from renewable sources. Biogas production, which will play a key role in future energy systems largely based on renewable sources, is expected to grow significantly in the next few decades. To achieve these ambitious targets, the biogas production chain has to be optimised to obtain economic viability and environmental sustainability while making use of a diversified range of feedstock materials, including agricultural residues, agro-industrial residues and, to some extent, dedicated energy crops. In this study, we integrated energetic, GHG and economic analysis to optimise biogas production from the co-digestion of pig slurry (PS) and sugar beet pulp silage (SB). We found that utilising SB as a co-substrate improves the energy and GHG balances, mostly because of increased energy production. However, utilising SB negatively affects the profitability of biogas production, because of the increased costs involved in feedstock supply. The scale of the processing plant is neutral in terms of profitability when SB is added. The results indicate that medium-to large-sized biogas plants, using low shares of SB co-substrate, may be the preferred solution.

1. Introduction

Anaerobic digestion (AD) is one of the most efficient technologies for extracting clean and renewable energy from biomass with high water content [1]. In addition, AD is useful for recycling nitrogen (N) and phosphorus (P) from animal manure, which is in great need worldwide [2,3], and it is also considered to be the most effective technology for reducing greenhouse gas (GHG) emissions from manure management and at a low cost [4,5]. AD is fully integrated into Denmark's long-term strategy to be independent of fossil fuels before 2050 [6,7]. In accordance with this strategy, 50% of all animal slurry must be used in AD by 2020 [8], and 60% of organic waste from public services (up from the current level of 17%) will be collected and utilised for biogas production by 2018 [9]. In 2050, biogas plants are expected to be processing about 42 PJ of biomass, corresponding to >7% of all energy input for Denmark, while 16–22% of all biomass will be routed to energy production [10].

Abbreviations: AD, anaerobic digestion; BMP, biochemical methane potential; CHP, combined heat and power; CSTR, continuous stirred tank reactor; EF, emission factor; GHG, greenhouse gases; HRT, hydraulic retention time; PS, pig slurry; SB, sugar beet pulp silage; TC, total cost; TI, total income; TNI, total net income; TS, total solids; VS, volatile solids; VS_D, degradable volatile solids; VS_{ND}, non-degradable volatile solids; ww, wet weight.

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The AD of animal manure is in focus for two reasons: 1) large amounts of manure are available in Denmark [11] and 2) it allows for the better management of N and P nutrients at the regional level. In Denmark, manure is currently collected in the form of slurry, with a water content of about 95% and an organic matter content of ca. 4% [12]. Owing to this high water content, manure can only be used at the present time for biogas production, though hydrothermal liquefaction may represent an alternative to anaerobic biogas production in the future. Manure has a low biogas production potential [13], meaning that its digestion needs to be boosted by a more energetic co-substrate [14]. Suitable co-substrates include other agricultural residues, organic industrial by-products (e.g. from the food industry) and dedicated bioenergy crops.

The amounts of biogas to be produced and the portfolio of biomass materials to be used represent important logistical and management challenges, the combination of which hinders environmentally sustainable and economic viable biogas production in the country. Environmental and energetic issues related to biogas production are depicted rather comprehensively in the available literature, focusing for example on the digestion and/or co-digestion of manure (e.g. Hamelin et al. [15]; De Vries et al. [16]; Lansche & Mueller [17]), municipal organic waste (e.g. Møller et al. [18]; Bernstad et al. [19]; Boldrin et al. [20]; Levis & Barlaz [21]), industrial co-products (e.g. Berglund & Börjesson [22]; Tufvesson et al. [23]), sewage sludge (e.g Tarantini et al. [24]; Lederer & Rechberger [25]; Nakakubo et al. [26]), energy crops and/or cropping systems (Amon et al. [27]; Gerin et al. [28]; Jury et al. [29]; Schumacher et al. [30]; Blengini et al. [31]; Buratti et al. [32]; González-García et al. [33]). These studies indicate that biogas production from residual biomass is generally environmentally beneficial, but the modelling of biogas from energy crops somehow seems more complex, as it must consider carefully local conditions regarding crop cultivation and the supply chain [34]. The economic viability and optimisation of biogas production has also been investigated in a number of studies (e.g. Walla & Schneeberger [35]; Power & Murphy [36]; Gebrezgabher et al. [37]; Karellas et al. [38]; Stürmer et al. [39]; Brown et al. [40]; Delzeit & Kellner [41]; Møller & Martinsen [42]; Riva et al. [43]; Schievano et al. [44]), indicating that the profitability of biogas production is generally related to factors such as the plant size, the cost of feedstock, initial investment, costs for storage and transportation and biogas yield.

The integration of environmental and economic assessments was only attempted in a few cases. Most of these studies – e.g. Murphy et al. [45], Ayoub et al. [46], Ayoub et al. [47], Luo et al. [48], Santibanez-Aguilar et al. [49], Hennig & Gawor [50] –, however, focus on the use of dedicated energy crops and their conversion in complex and centralised biorefinery systems used for fuel production. Biogas production from residual materials is investigated, for example, in Yabe [51]. These studies nonetheless are static in nature, as the assessments are carried out at the scenario level. When looking at the co-digestion of residual biomass and energy crops, no studies were found to have attempted to optimise biogas production by dynamically modelling individual sub-parts of the biogas chain.

Therefore, the objective of the study presented herein is to develop a joint value-chain, energy and environmental model, to be used for optimising biogas chain production. This model is meant to provide advice to managers and decision makers in the form of a holistic evaluation of risks and benefits in producing biogas using sugar beet pulp silage (SB). This objective is achieved by 1) developing detailed economic, GHG emission, energy and mass models for the biogas chain, 2) integrating these models into a single framework capable of describing the relationships between economy, energy and emissions, while taking into consideration scaling effects, 3) applying the model to optimise the use of beet roots in manure co-digestion and 4) identifying the optimal scale of the biogas plant.

2. Materials and methods

2.1. The biogas production chain

As shown in Fig. 1, the biogas production chain assessed herein consists of five main process units, including:

- Raw material input: cultivation and harvesting stages
- Pre-treatment: washing, slicing and ensiling
- Transportation: transportation to the biogas plant and transportation to the farm
- Energy production: mixing tank, anaerobic digester, post-digestion plant and combined-heat-and-power (CHP) plant or gas upgrade for the gas transmission net
- Digestate process and fertiliser unit: after-storage and field stages

SB is first cultivated and then harvested between September and mid- or late November [52]. While harvesting, the root is separated from the beet top and left on the field. Beet roots carry a significant amount of soil, and so a cleaning step is thus required. Cleaning is normally performed at the farm level, but centralised cleaning can occur in some cases. The soil removed from the root is returned to the field. SB harvested in November are then stored in clamps covered with straw [52]. In February, the roots are chopped finely into beet pulp and moved into silos for 18 months (i.e. until September next year). Ensiling leads to the degradation of some organic pools, so that total solids (TS) and volatile solids (VS) contents change, while GHG are emitted. When needed, SB is collected and then mixed with pig slurry (PS) to a known ratio, and the mixture is then pumped into an AD reactor. PS is the main substrate, whereas SB is the co-substrate providing different benefits to the process: it contains abundant trace elements for microbial growth, it has a strong buffer capacity, thereby helping to maintain pH neutrality, and it is a good diluter for toxic compounds potentially contained in the manure. In the present study, the co-digestion of three mass-based ratios of PS and SB in the feedstock is analysed:

- PSSB-0: 100% PS, 0% SB
- PSSB-12.5: 87.5% PS, 12.5% SB
- PSSB-25: 75% PS, 25% SB

The additional use of SB (i.e. a 50/50 ratio) was attempted in preliminary tests; however, the AD operation was unstable with the accumulation of VFAs and a drop in pH level.

The main product of the digestion process is biogas (i.e. a mix of CO_2, CH_4 and other trace gases), which can be used for electricity and/or heat production, or fed to the natural gas grid. Depending on the final recipient and the energy conversion technology employed, biogas may need to be upgraded to remove most of its CO_2 and other trace compounds. The by-product of the digestion process is a type of slurry called “digestate,” which is typically partly dewatered and further stabilised by means of aerobic composting. The finally cured digestate may be stored further until its final application to agricultural land as a fertiliser and soil amendment agent. The calculations herein considered a field-application scenario where digestate is applied in early spring, prior to seeding a spring cereal crop.

In the biogas production chain, the economy of scale can be a significant factor affecting the profitability of a project. In fact,

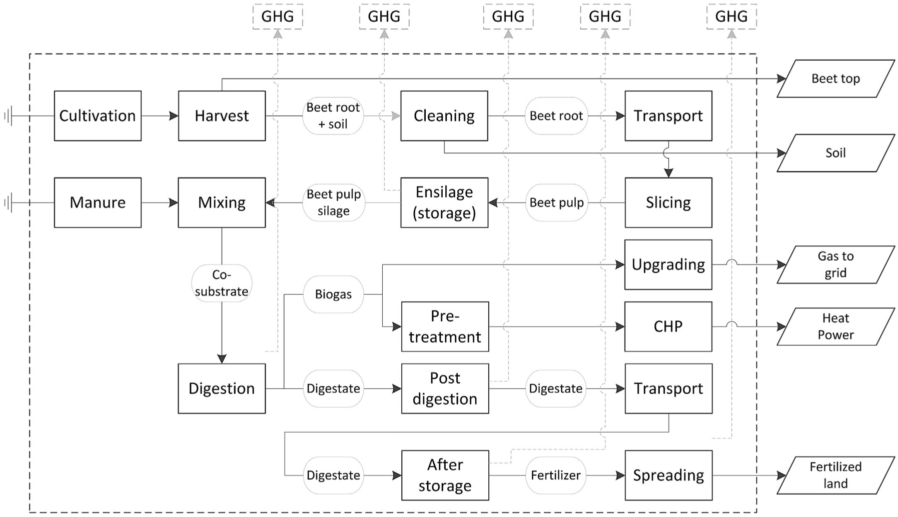

Fig. 1. Overview of the biogas chain model.

while production costs per unit of biomass handled may be reduced in large facilities, transportation costs may increase significantly, due to the larger size of the catchment area for the biomass. To assess the scale effect, economic analysis was thus performed on three facilities: small (i.e. using 110,000 Mg of biomass per year), medium (i.e. 320,000 Mg/year) and large (i.e. 500,000 Mg/year). The size of the plant is assumed not to have an effect on mass and energy balances.

2.2. The mass balance model

We based mass balance calculations on both the literature and experimental data. Input and outputs from individual processes in the biogas chain were modelled by tracking digestible (VS_D) and non-digestible (VS_{ND}) components of VS. In the model, we defined lignin as VS_{ND}, as it is non-degradable in an anaerobic environment [13]. The remaining VS (i.e. total VS minus lignin) was defined as VS_D. The basis for the mass balance calculation was 1000 kg of feedstock fed into a biogas digester. The mass balance model included stages shown in Fig. 1, as explained in the previous section. We reconciled and displayed mass and energy balances using STAN, a software package used for material and substance flow analysis [53].

For the harvested SB, we used data from Schoups et al. [54] and Thalbitzer [55], to determine mass distribution into roots, tops and soil. Harvested beet root accounted for 70.7% of the total mass, whereas beet tops were 25.6% and soil 3.8%. The total solids (TS) in the root were 226 g/kg, and VS was 208 g/kg. While the top is removed, the root and attached soil are moved further on to the cleaning step. The amount of soil left after the wet washing step was assumed to be 2.1% of TS. Since soil contains mostly ash (85% in TS), the VS concentration is slightly lower than the case where the root is without soil.

We assumed the pulping process would involve no mass loss, and we modelled the storage process for the beet root as employing two sub-processes, both responsible for significant VS degradation (i.e. ~28% and 12% respectively, Table S2 in supporting information) and any subsequent decrease in biogas production during AD. For the sake of simplicity, the two storage sub-processes were represented by one overall storage process in the mass balance model.

We experimentally measured the composition of SB and PS, as well as biogas production data during AD from different sources (details provided in the supporting information). We carried out physicochemical analysis of PS and SB according to the standard procedure (APHA standard method [56], see supporting information), and we determined biochemical methane potential (BMP) according to VDI 4630 (2006). We also investigated the AD of different feedstock mixes using a 20 L continuous flow stirred-tank reactor (CSTR) in a mesophilic condition (37 °C), with a hydraulic retention time (HRT) of 20 days. Data for the individual co-digestion mixing ratios are presented in Table 1, where it is evident that contributions of VS from SB and PS are considerably different for the analysed scenarios. For example, in the PSSB-25 scenario, 58% of VS is from SB while 42% is from PS, while approximately 63 and 37% of VS originates from SB and PS, respectively, in the PSSB-12.5 ratio. The prime feedstock (i.e. PS) had BMP of 296 NL_{CH4}/kg_{VS} (9.42 NL_{CH4}/kg_{ww}). The BMP of SB was 424 NL_{CH4} kg/kg_{VS} (54.8 NL_{CH4}/kg_{ww}). During CSTR experiments, 43.4–55.9% of VS was transformed into biogas (supporting information, Table S5). When only PS was digested, CH_4 production was 9.10 CH_4NL/kg_{ww}, while CH_4 productions from the PS and SB mixtures were 12.3 NL_{CH4}/kg_{ww} and 18.0 NL_{CH4}/kg_{ww} for PSSB-12.5 and PSSB-25, respectively. Using the equation provided by Sommer et al. [4], methane emissions post-storage were estimated at 0.30–1.99 NL_{CH4}/kg_{ww}. Additional details are provided in the supporting information.

Table 1
Composition of co-feedstock and biochemical methane potentials (BMP) for biogas production at different co-digestion mixing ratio scenarios.

Parameter	Unit	PSSB-0	PSSB-12.5			PSSB-25		
		PS	PS	BS	Co-feed	PS	BS	Co-feed
Wet mass	g	1000	875	125	1000	750	250	1000
TS	g	37.7	33.0	22.4	55.4	28.3	44.9	73.2
	% ww	3.8	3.8	17.9	5.5	3.8	17.9	7.3
Water	g	962	842	103	945	722	205	927
	% ww	96.2	96.2	82.1	94.5	96.2	82.1	92.7
VS	g	31.8	27.8	16.2	44.0	23.9	32.3	56.2
	% TS	84.4	84.4	72.0	79.4	84.4	72.0	76.8
Ash	g	5.9	5.2	6.3	11.4	4.4	12.5	17.0
	% TS	15.6	15.6	28.0	0.0	15.6	28.0	0.0
VS pools								
VS_D	g	28.2	24.7	13.8	38.5	21.1	27.6	48.7
	% VS	88.6	88.6	85.3	86.7	88.6	85.3	86.7
VS_{ND}	g	3.6	3.2	2.4	5.5	2.7	4.8	7.5
	% VS	11.4	11.4	14.7	13.3	11.4	14.7	13.3
Biogas potential								
BMP	NL_{CH4}/kg_{VS}	296	296	424	342	296	424	370
	NL_{CH4}/kg_{WW}	9.4	9.4	54.8	15.1	9.4	54.8	20.8

PS: pig slurry; SB: sugar beet pulp silage; VS_D: degradable VS; VS_{ND}: non-degradable VS; ww: wet weight; TS: total solids; VS: volatile solids; BMP: biochemical methane potential.

2.3. The energy balance model

For individual flows of materials in the system, we assumed an energy content (H_{aw}, ash- and water-free) of 20.5 MJ/kg_{VS} and 26.6 MJ/kg_{VS} for the VS_D and VS_{ND} respectively. As specific data for VS_D and VS_{ND} does not exist, we derived these values through data reconciliation, in order to fit the energy balance with respect to the energy content of the inputs, outputs and biogas production. These estimated values are in accordance with data reported for cellulose/hemicellulose and lignin materials. Energy related to the cultivation and harvesting of sugar beet was 0.334 MJ/kg, taken as cumulative energy demand for the Ecoinvent (v2.2) process 'Sugar beet, from farm'. We assumed the production of PS as being burden-free, meaning that energy and material consumptions utilised for animal growth were excluded from the calculation.

For transportation, we based diesel consumption on estimated driven distances (see later) and assumed a consumption factor of 0.02645 l/tkm (Ecoinvent process 'Transport, lorry >32t, EURO5'). For the energy balance, we assumed that diesel has an energy content of 43.1 MJ/kg, a density of 0.832 Mg/m^3 and a cumulative primary energy content of 54.8 MJ/kg (Ecoinvent process 'Diesel, low-sulphur, at regional storage'). We estimated energy consumption during ensilage at 150 MJ/Mg and 6.7 MJ/Mg, based on Ecoinvent processes 'Baling/CH' and 'Loading bales/CH', respectively, and assumed that each bale contained ~1.3 Mg of beet root. The spreading of digestate on land requires 0.26 L/m^3 of diesel (Ecoinvent process 'Slurry spreading, by vacuum tanker').

We estimated electricity consumption for operating the biogas plant at 30 MJ/Mg [22], while the energy requirement for heating up the feedstock was estimated at 121 MJ/m^3 of slurry (or 1800 MJ/Mg_{TS}). For the estimation, we assumed that the average temperature of the inlet material was $T_{in} = 8$ °C and that the slurry had a density and specific heat similar to water (i.e. 1000 kg/m^3 and 4.19 kJ/kg/K); additional details are provided in the supporting information. The biogas produced is combusted in an engine (i.e. Jenbacher 420), with conversion efficiencies of 40 and 42% for electricity and heat, respectively [57]. Part of the produced energy is used for operating the plant, while the surplus of electricity and heat is delivered, respectively, to the electricity network and district heating facilities. For electricity, cumulative primary energy was assumed at 2.47 $MJ/MJ_{electricity}$, as in ELCD process 'Electricity mix, AC, consumption mix, at consumer, 1kV-60 kV DK'. For heat, cumulative primary energy was assumed at 1.55 MJ/MJ_{heat}, as reported by the Danish Energy Agency [58].

2.4. The GHG model

We established the GHG balance using the conversion factors for diesel combustion, electricity and heat (reported in Table 2) applied to the individual energy inputs described previously. The loss of biogas due to fugitive emissions from the plant is rather uncertain, as very few measurement studies at full-scale plants have been conducted so far. In the present study, we assumed that the fugitive emission of CH_4 corresponds to 3.1% of the CH_4 production in the biogas plant, as estimated by Flesch et al. [59] for an agricultural biodigester, including storage of the digestate.

We predicted the short-term emission of N_2O using the N_2O sub-model developed by Sommer et al. [4], which considers N_2O emission to be a function of VS in slurry or digestate, reactive slurry nitrogen (N) and soil water potential (ψ). As explained in the supporting information, the model makes use of the VS_D and VS_{ND} introduced in section 2.2. For model calculations of N_2O emissions, we assumed an application rate of 100 kg NH_4^+-N/ha. Following Sommer et al. [4], the nitrification of reactive N in slurry hotspots was assigned an N_2O emission factor (EF) of 0.5%, and the nitrification of N from digestate or slurry in the surrounding soil was allocated an EF of 0.2%. We calculated total denitrification in the slurry clumps as a function of VS_D in the hotspot, and the resulting N_2O emission was estimated by assuming an EF of 2%. Total N_2O emissions produced by nitrification in clumps and soil, and by denitrification in clumps, were expressed on an area basis but also relative to slurry/digestate VS. The calculation considered a field-application scenario where slurry/digestate is applied in early spring, prior to seeding a spring cereal crop. We assumed an NH_3 loss of 10% during application, and soil-water potential was set to −0.015 MPa, i.e. close to field capacity.

We estimated VS_D in digestate and untreated feedstock from the short-term evolution of CO_2-C after incubating slurry/digestate in soil under aerobic conditions. We assumed that VS_D in applied materials would be fully degraded when CO_2 evolution rates became constant. The six incubation tests included three samples of digested material, two samples of raw feedstock and one control (i.e. only soil); each test included five replicates. The digestate samples were produced in CSTR experiments, as explained in

Table 2
Emissions factors for energy inputs to the biogas chain.

Process	Unit	Amount	Note, reference
Diesel combustion	kg CO2-eq/liter	3.1	Provision + combustion (Fruergaard et al., 2009)
Electricity production	kg CO2-eq/kWh	0.95	Hard coal, NORDEL (Fruergaard et al., 2009)
Heat production	kg CO2-eq/GJ	72	District heating, natural gas (Fruergaard et al., 2009)

section 2.2. The three samples of digestate corresponded to feedstock mixtures previously described (i.e. PSSB-0, PSSB-12.5, PSSB-25), while the two samples of raw feedstock included undigested PS and SB. The main physicochemical properties of the materials used for the incubation tests are reported in the supporting information (Tables S3 and S8), together with a description of the experimental setup (Table S7), the gas sampling procedure, the data analysis and the estimation of N_2O emissions for the analysed scenarios (Table S9 and Table S10).

We converted the emissions of different gases to CO_2-equivalent emissions, by using the following 100-year global warming potentials (GWPs): 1 kg CO_2eq/kg CO_2 for fossil CO_2, 28 kg CO_2eq/kg CH_4 for biogenic CH_4, 30 kg CO_2eq/kg CH_4 for fossil CH_4, 265 kg CO_2eq/kg N_2O for N_2O (according to IPCC [60]) and 0 kg CO_2eq/kg CO_2 for biogenic CO_2 [61].

2.5. The economic model

In the following, the economic model is described briefly, while additional details are provided in supporting information. The objective of the economic model was to determine the total net income (TNI) of different scenarios, where we define the $TNI(p_k,M_j,M_k,r_j,j_k)$ as (Equation (1)):

$$TNI(p_k,\ M_j,\ M_k, r_j,\ j,\ k)\ =\ TI(p_k,\ M_k) - TC(M_j, M_k, j, k) \tag{1}$$

where $TI(p_k,M_k)$ is the total income as a function of the price p_k of output k and the mass M_k of output k; $TC(M_j,M_k)$ is the total cost as a function of the mass M_j of biomass j and the mass M_k of output k and the index j and k are objects of the set J of input biomass (i.e. PS and SB) and the set K of output (i.e. digestate, biogas), respectively.

2.5.1. Income

Total income $TI(p_k,M_k)$ is the sum of the prices paid for the different outputs and is defined as (Equation (2)):

$$TI(p_k,\ M_k) = \sum_{k \in K} p_k M_k \tag{2}$$

where M_k is the mass of output k (i.e. digestate, M_{dig}, biogas, M_{gas}) and p_k is the price of output k.

The factor M_k is a function of the process yield, which is in turn a function of different operational parameters, such as feedstock composition and HRT in the process, as explained and estimated in section 2.2. We estimated the prices p_k of the digestate (p_{dig}) and biogas (p_{gas}) based on market considerations. In an agricultural context, digestate has some value because of its fertilising potential and reduced smell in the area. The p_{dig} depends on the specific supplier agreement between the operator of the biogas plant and farmers, thereby including the requirement of the farmer to dispose of the PS.

We estimated p_{gas} in Denmark based on the final use of the biogas and the level of public support. We considered the following two options:

- Biogas is upgraded and fed to the natural gas network.
- Biogas is used locally in a combined heat and power (CHP) plant.

When biogas production exceeds a specific amount, hereby estimated as 3.5 million m^3 per year, it was calculated that biogas was upgraded and fed into the natural gas grid. In this case (Equation (3)), the selling price of the biogas ($p_{gas,UP}$) is determined by the market price for the natural gas (p^{NG}), the support level (S) and a potential green factor (p^g), corresponding to the market price for "being green", determined from sales of green certificates.

$$p_{gas,UP}\ = p^{NG} + p^g + S \tag{3}$$

When biogas is used at a CHP plant, its price ($p_{gas,CHP}$) is a combination of the price of biogas as such and a market power value, as shown in (Equation (4)):

$$p_{gas,CHP} = p(p_{NG}, S,\ p_{HP}) - p_{MP} \tag{4}$$

where p_{NG} is the price of natural gas, S is the level of public support given to the CHP, p_{HP} is the price of heat and power generated and sold to the market and p_{MP} is the market power value, which depends on the structure of the power market (e.g. user and supplier are monopolist, or alternative supply/production options exist).

2.5.2. Costs

From the biogas plant perspective, total cost $TC(M_j,M_k)$ is expressed as (Equation (5)):

$$TC(M_j, M_k) = C_{trans}(M_j, M_k, GP_k) + C_{opex}(M_j, M_{gas,UP}) + C_{capex}(M_j, M_k) \tag{5}$$

where $C_{trans}(M_j,M_k,GP_k)$ is the transport cost, $C_{opex}(M_j,M_{gas,UP})$ is the operational cost and $C_{capex}(M_j,M_k)$ is the cost of investments. The C_{trans} is a combination of the costs borne for transporting PS and SB to the AD plant, as well as the costs for transporting digestate and biogas away from the plant, as shown in Equation (6).

$$C_{trans}(M_j, M_k, GP_k) = C_{trans,in}(M_j) + C_{trans,out}(M_{man}, M_k, GP_k) \tag{6}$$

where $C_{trans,in}$ represents the cost of transporting the PS/SB to the AD plant and $C_{trans,out}$ is the cost related to the transportation of digestate and biogas away from the AD plant.

The size of the plant will hence influence transportation costs significantly, as a larger plant will involve longer driving distances, to ensure the supply of the required biomass. To estimate transportation distances according to the size of the plant, the supply area was modelled using concentric circles around the biogas plant, whereby availability and supply cost of PS/SB could be estimated as a function of the radius (i.e. the distance from the plant). With respect to digestate transportation, it was considered that a share of the digestate could be transported back to the some farmers delivering PS. The maximum amount that could be returned to individual farmers was set to 115% of the PS they delivered; any excess sludge would involve additional costs for its transportation to other farmers. A detailed description of the calculation is provided in the supporting information.

Operational expenditures (C_{opex}) for the biogas plant are estimated as follows (Equation (7)):

$$C_{opex}(M_j, M_{gas,UP}) = C_{opex,input}(M_j) + C_{opex,oper}(M_j, M_{gas,UP}) \quad (7)$$

where $C_{opex,input}$ represents the cost of buying PS/SB beet according to the market prices and $C_{opex,oper}$ is cost related to operating the biogas plant, including the following factors (Equation (8)):

$$C_{opex,oper}(M_j, M_{gas,UP}) = C_{basis}\left(\sum_{j\in J} M_j\right) + (C_{wear} + C_{pow} + C_{man}) \cdot M_{sug} + C_{opex,UP}\left(p_{pow}, M_{gas,UP}\right) \quad (8)$$

where C_{basis} is the basis cost of a biogas plant with size $\sum_{j\in J} M_j$, C_{wear} is the cost of wear per Mg of SB, C_{pow} is the cost of power per Mg of SB, C_{man} is the cost of manpower per Mg of extra SB and M_{sug} is the total mass of SB. $C_{opex,UP}$ is the cost for biogas upgrading, which is a function of the amount of biogas upgraded ($M_{gas,UP}$) and the price of power (p_{pow}).

Investment costs (C_{capex}) depend on investments related cost-wise to input, production and output. As in this model it is assumed that all transportation is rented (i.e. no investment costs for trucks and other), and the C_{capex} is defined as (Equation (9)):

$$C_{capex}(M_j, M_k) = C_{capex,prod}(M_j) + C_{capex,output}(M_j, M_k) \quad (9)$$

where $C_{capex,prod}$ is the investment cost for production, including the biogas plant, the process heat boiler, the purchase of land, counselling and other elements, and $C_{capex,output}$ is the investment cost for output, including the storage of digestate, the storage of biogas and the biogas cleaning/upgrading facility. The depreciation time for the biogas facility is assumed being 20 years, as recommended by Ea Energianalise to the Danish Energy Agency [62].

3. Results and discussion

3.1. Mass and energy balance

We reconciled mass balances for the PSSB-0, PSSB-12.5 and PSSB-25 feedstock mixtures, including wet weight, TS and VS. An example of mass balance for PSSB-12.5 is presented in Figs. 2 and 3, while remaining figures are provided in the supporting information (section 4).

We found that, when looking at the wet mass, PS represents the most significant flow in all of the scenarios analysed. However, when SB is added to the feedstock in scenarios PSSB-12.5 and PSSB-25, this flow represents the major input of VS and TS into the system. We found similar results in the energy balance (Fig. 4), indicating that, as expected, even a relatively small addition of SB significantly increases the throughput of energy in the system while significantly boosting biogas yield (both total production and yield per Mg of input). PS indeed represents a preferable mean for diluting the high content of solids in SB instead of freshwater: besides the significant savings of water resources (and connected expenses), the use of PS as a prime co-substrate provides better nutrient balancing and increased buffering capacity.

Digestate represents the main output of the system, regardless of the feedstock mixture considered, the reason being the substantial amount of water carried as a result. With regards to VS, the situation is rather different, as the majority of VS is converted into gaseous compounds during the AD process. While biogas is used for energy production, the significant amount of gas forming during ensiling represents a loss of energy within the system; this loss, however, is almost unavoidable, as SB storage is needed to ensure the supply of feedstock to the reactor throughout the whole year. The addition of SB to the feedstock mixture has a clear effect on biogas production (per unit of input), which almost doubles – going from PSSB-0 to PSSB-25 (Table 3). This result is a combination of three aspects: an increase in the BMP of the input (Table 3), an increase in VS content in the feedstock (from 3.2% ww in PSSB-0 to 5.6% ww in PSSB-25) and a decrease in the ratio between biogas yield and the BMP (Table 3). The latter suggests that, when adding SB, some adjustments in the digestion process HRT may be needed, to exploit further the methane potential of the feedstock material.

VS degradation throughout the whole biogas chain is in the order of 45%–68% (Table 3) of VS input into the system, whereas VS degradation within the digestion process is in the order of 43–56%. This figure is in line with what was reported by Møller et al. [18] for cattle manure (i.e. 21–44%) and pig manure (i.e. 47–78%), while it is lower than findings for other substrates (e.g. 53–80 in Marañón et al. [63], Gebrezgabher et al. [37], Schievano et al. [64], Delzeit & Kellner [41]). The results in Table 3 show that, with a fixed HRT, the addition of SB as a co-substrate decreases CH_4 yield (as percent of

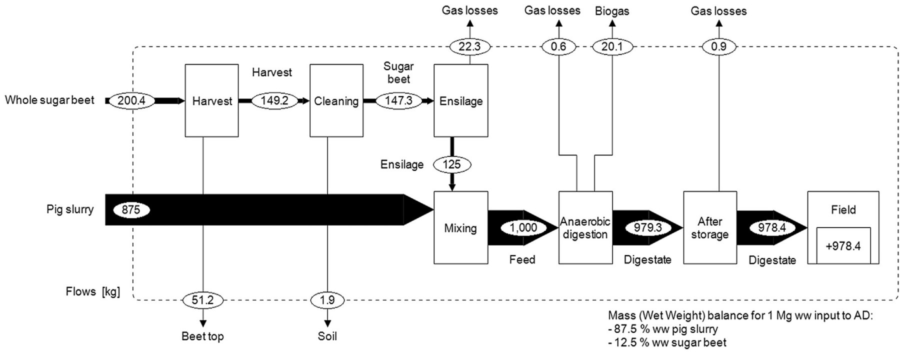

Fig. 2. Mass (kg, wet weight) balance of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-12.5, i.e. a mix of PS (87.5% ww) and SB (12.5% ww).

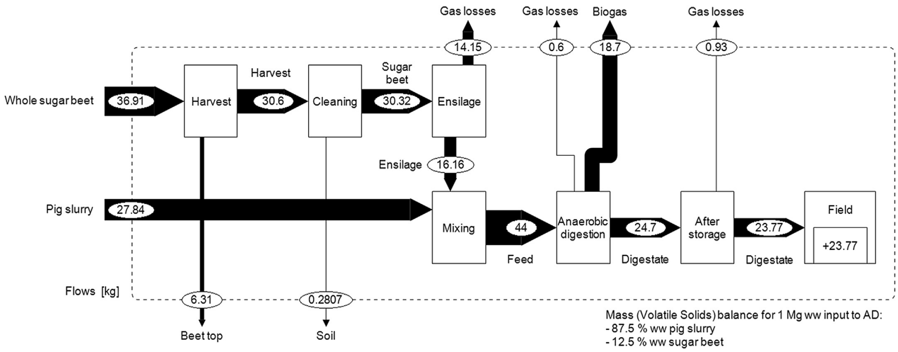

Fig. 3. VS (kg) balances of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-12.5, i.e. a mix of PS (87.5% ww) and SB (12.5% ww).

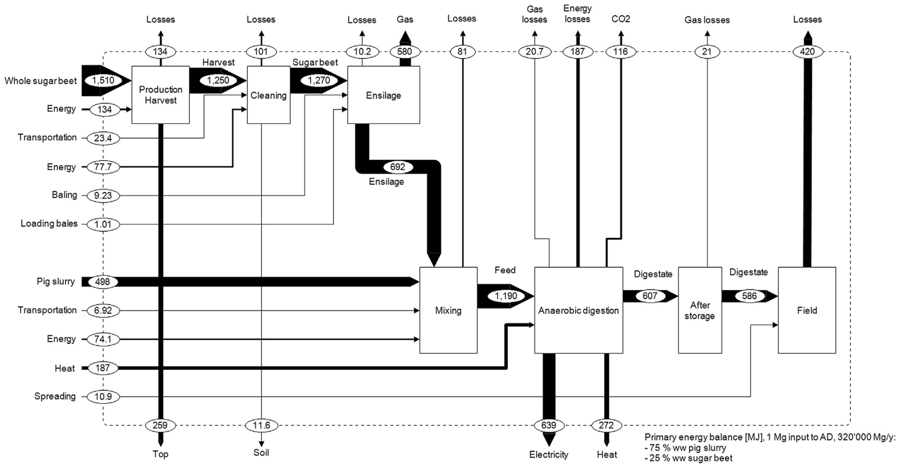

Fig. 4. Energy balance (MJ of primary energy) of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-25, i.e. a mix of PS (75% ww) and SB (25% ww), while the size of the plant is 320,000 Mg/y.

Table 3
Overview of key parameters for the modelling of biogas production.

Parameter	Unit	PSSB-0	PSSB-12.5	PSSB-25
CH_4 yield	m^3/Mg_{ww} input	9.10	12.3	18.0
CH_4 yield	m^3/Mg_{VS} input	296	343	369
CH_4 yield	% of BMP	96.6	82.2	87.6
CH_4 concentration	% in biogas	57.2	57.1	57.2
VS degradation – system	% VS input to the system	44.8	66.4	67.6
VS degradation – digestor	% VS input to the digestor	43.5	55.6	51.2
VS_{ND} in digestate	% of total VS	20.6	29.4	27.8

the BMP), while the overall VS degradation increases slightly. This is due to the fact that SB contains a larger amount of slowly degradable VS, which in turn possibly requires longer HRT to reach high yields. In general, a significant share of the VS in the digestate is non-degradable in anaerobic conditions (i.e. 21% for PSSB-0, 17% for PSSB-12.5, 28% for PSSB-25).

3.2. GHG balance

Our findings show that increasing the share of SB in the feedstock mix results in a significant decrease in N_2O emissions from land application (Table 4). This is due to the fact that adding SB to the mix enhances both the C content and the C:N ratio of the digestate, thereby increasing CO_2 production and decreasing the formation of N_2O per unit of VS added (see supporting information, section 2.2).

An overview of GHG emissions from the analysed system is presented in Table 5, according to individual sub-processes in the biogas chain. We found that fugitive emissions of gases from the digestion process, and the storage and application on land of digestate, represent a significant contribution to the overall GHG balance (i.e. between 33 and 44% of direct emissions). Because of a lack of data, some of these estimations may, however, be associated with significant uncertainty. For example, in the present study we assumed fugitive emissions from digestion in the order of 3.1% of the produced biogas; however, other studies indicate that such a value may be subject to significant variability. For example, fugitive emissions in the order of 0.3–2.6% were estimated by Liebetrau et al. [65] for 10 agricultural biogas plants in Germany, and 2.1–4.4% were estimated by Yoshida et al. [66] for a biogas plant treating wastewater treatment plant sludge in Denmark. However, it is generally not well-clarified whether the age/technology of the biogas plant, as well as the feedstock material, has an influence on these emissions. The operation of the digester (i.e. pumping, heating, etc.) also makes some significant contribution to the overall GHG balance, in the order of 16 kg CO_2eq/Mg of feedstock. The use of SB as a co-substrate also significantly influences overall GHG emissions, in that it makes a significant contribution to direct emissions, albeit this is completely counterbalanced by increased biogas production. Energy production (i.e. electricity and heat) from biogas is the most important element in the GHG balance, as it may offset energy production somewhere else in the system (i.e. the results in Table 5 are displayed as negative contributions). In this context, the choice of the alternative source of energy production (herein coal, see Table S6 in supporting information) may have a significant influence on the results.

The results in Table 5 show that, regardless of the size of the plant and the subsequent distance driven, transportation does not make significant contribution to direct GHG emissions. This represents a substantial inconsistency compared with results regarding bioenergy production based solely on energy crops, where transportation did matter, as driven distances were much longer (e.g. Boldrin & Astrup [67]), while highlighting the importance of both using biomass residues and carefully selecting the location of the biogas plant to ensure the availability of locally (short distance) produced biomasses.

3.3. Economic analysis

We estimated total income (TI) for the biogas plant in the range 17.3–24.9 €/Mg of input into the biogas plant (Supporting Information, Table S33). Gas subsidies have a significant influence on income (Fig. 5 and Fig. S8), while market revenue for energy products is less pronounced. Without subsidies, the TNI of biogas production would be negative, thus confirming previous findings (e.g. Gebrezgabher et al. [37], Delzeit & Kellner [41], Mafakheri & Nasiri [34]). This highlights the importance of future support policies for the sustainability of biogas production in Denmark. Our findings show positive signs of economies of scale, whereas the composition of the feedstock has an even greater effect on the results, as increasing the utilisation of SB significantly enhances biogas production, albeit not enough to outweigh increased costs related to the SB.

We estimated total costs (TCs) for the biogas production chain in the range 15.8–26.5 €/Mg of input into the biogas plant (supporting information, Table S35). Costs, to a high degree, are connected to the feedstock supply, as the price of manure is closely linked to an agreement with farmers, whereby manure is returned in a treated form as digestate; feedstock costs are considered here only as SB costs and account for 0–39% of the costs, depending on the share of SB utilised (see Fig. S9 for details). This figure is in the lower range compared with previous findings by Schievano et al. [44] for maize (i.e. 40–62%), rye (i.e. 54–67%), triticale (i.e. 34–48%) and sorghum (i.e. 49–62%) cultivated in a Mediterranean climate. Particularly in the PSSB-0 cases, the positive scale effect on capital costs (C_{capex}) becomes clear, while operational costs (C_{opex}) dampen the economy of scale effect. The TC is significantly influenced by both the feedstock mix and the scale of the plant. In fact, the SB is so costly that it becomes the most important cost factor in the PSSB-25 cases. Moreover, the utilisation of SB also has an influence on the costs of transportation (which can add up to 20% of TC), as longer distances need to be covered to guarantee the supply of SB for biogas production. The scale of the plant also influences transportation and C_{capex} costs, as an increase in plant size requires a larger supply of feedstock with a subsequent increase in driven distance, which varies in the range 5.5–10.3 km for PS and 0–70.4 km for SB (supporting information, Table S15), depending on the plant size. These figures, however, depend strongly on local farming types (e.g. animal, plant), thereby suggesting that decision making should be based on regional considerations. We estimated costs for transportation in the range 1.1–4.1 €/Mg, with lower figures associated with small-scale plants not making use of SB. These values are in line with what is reported by, for example, Walla & Schneeberger [35]. Capital costs (C_{capex}) are estimated in the range of 3.1–5.2 €/Mg (supporting information, Table S36), with lower figures referring to large-scale plants. We estimated operation costs (C_{opex}) in the range 3.3–4.3 €/Mg (Table S36). The size of the plant has rather a small influence on the C_{opex}, while C_{opex} does increase when introducing SB to the feedstock, as additional manpower is needed for handling SB (additional details in supporting information).

An overview of total net income (TNI) is shown in Table 6. Based on existing subsidies, price assumptions for inputs and outputs and

Table 4
Emissions of N_2O from applying different digestates on land (NH_3 loss 10%, soil water potential −0.015 MPa).

Treatment	N_2O [g N_2O/kg$_{VS,applied}$]	N_2O from NH_3 loss [g N_2O/kg$_{VS,applied}$]	Total N_2O [g N_2O/kg$_{VS,applied}$]
PSSB-0	0.66	0.17	0.83
PSSB-12.5	0.59	0.12	0.71
PSSB-25	0.45	0.06	0.50

Table 5
Overview of GHG emissions [kg CO_2eq/Mg input] throughout the biogas production chain.

Stage	Process	GHG emissions [kg CO_2eq/Mg input]		
		PSSB-0	PSSB-12.5	PSSB-25
SB production	SB production		11.3	22.5
SB transportation	110,000 Mg/y		0.68	1.37
	320,000 Mg/y		1.04	2.08
	500,000 Mg/y		1.12	2.25
PS transportation	110,000 Mg/y	0.59	0.52	0.44
	320,000 Mg/y	0.82	0.72	0.61
	500,000 Mg/y	1.01	0.89	0.76
SB pre-treatment and storage	Washing		4.15	8.31
	Baling		0.71	1.42
	Loading bales		0.05	0.09
Anaerobic digestion	Milling + pumping	7.9	7.9	7.9
	Heat to digester	8.7	8.7	8.7
	Electricity production	−34.4	−46.7	−68.3
	Heat production	−9.9	−13.4	−19.6
	Biogas fugitive losses	5.6	7.6	11.2
Digestate storage	Gas losses	5.9	8.0	11.4
Application on land of digestate	Spreading	1.2	1.2	1.1
	N_2O in field	4.0	3.7	4.0

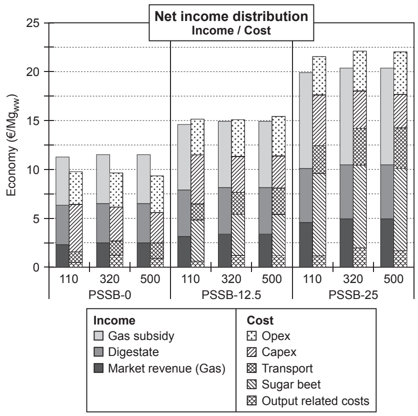

Fig. 5. Distribution of total income (TI) and total costs (TC) per Mg of input to the biogas plant.

the production technology (biogas yield), the only viable input composition is a feedstock containing 0% of SB (i.e. PSSB-0). In this case the largest plant is the most profitable. Scenarios including SB utilisation as a feedstock (i.e. PSSB-12.5 and PSSB-25) result in negative TNI, as costs are greater than income, due to the fact that increasing costs related to SB input are not counterbalanced by

Table 6
Overview of total net income (TNI) [€/Mg] for the biogas chain, according to plant size and input mixture.

Treatment	Unit	Plant capacity (1000 Mg)		
		110	320	500
PSSB-0	€/Mg	1.52	1.88	2.18
PSSB-12.5	€/Mg	−0.54	−0.17	−0.50
PSSB-25	€/Mg	−1.64	−1.74	−1.66

increased biogas production and any associated revenue. Conversely, for the entirely PS-based case (i.e. PSSB-0), the result is positive, meaning that incomes exceed costs. The size of the plant does influence the TNI to some extent, in particular because of the costs associated with transportation (i.e. the larger the plant, the greater the distance) and investment (i.e. the larger the plant, the smaller the investment per unit input). The results presented in Table 6 differ from what was estimated by Delzeit and Kellner [41], as our figures indicate that large-scale facilities have a fundamental potential for better profitability compared with small-scale facilities. For those cases with SB, the benefits of increasing scale are not clear, as we find that the TNI per unit of input is almost neutral in relation to scale.

3.4. Comparison

Results for energy balance, GHG emissions and TNI are presented comparatively in Fig. 6, in which it is evident that utilising SB is a major factor influencing the results of the energy, GHG and economic analyses. However, a univocal conclusion cannot be drawn, because while the energy and GHG analyses may suggest that the utilisation of SB as a feedstock into the biogas plant may prove beneficial, the economic analysis indicates that this may be too costly in the long run. As previously described, the only viable input composition is a feedstock containing 0% of SB (i.e. PSSB-0), whereas increasing utilisation of SB results in negative TNI.

The scale of the plant has little influence on the energy and GHG balances, as also indicated in previous studies (e.g. Stephenson et al. [68]); the scale, however, significantly affects net income, while if the biogas plant is operated using solely PS as a substrate, a large-scale plant may be preferable. If an SB co-substrate is employed, it becomes less clear what is preferable. A similar conclusion was reached by Walla & Schneeberger's [35] study of biogas production in Austria using maize silage as feedstock.

With respect to the results in Fig. 6, we found that the most critical assumptions and main uncertainties are related to the price of SB (relative to manure) and biogas yield in the AD plant. The price of SB is about 4.5 times higher than the PS one. In general terms, production costs for energy crops must be reduced to make biogas production profitable [35,37,44]. The increased biogas yield obtained when using SB as a substrate results in better energy and GHG balances, but it does not compensate for increased costs, due to the larger input costs of SB. Biogas yield is indeed a very critical

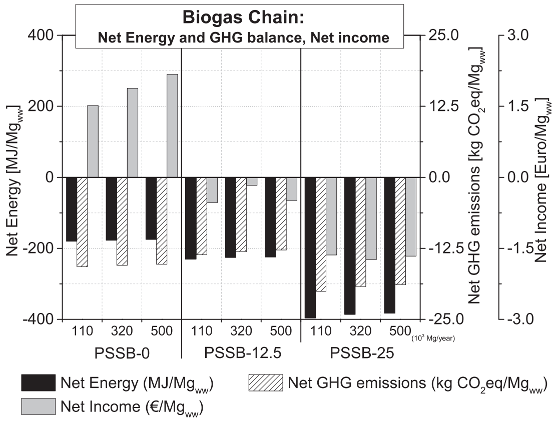

Fig. 6. Comparative overview of net energy balance (MJ/Mg), net GHG balance (kg CO_2eq/Mg), and Net Income (€/Mg) per Mg ww of input to the biogas plant.

factor for profitability. To reverse negative results for the TNI in Fig. 6, a further increase in gas yield (i.e. 5% for PSSB-12.5 and 13% for PSSB-25) is needed, thus suggesting that further optimisation of the process is required. The profitability of large-scale facilities seems more affected by biogas yield, as increased biogas generation would allow counterbalancing the costs for longer transportation journeys. In general, improving biogas yield may play an important role in relation to the profitability of biogas production [34,41,67].

Our results (Fig. 6) seem to indicate that the low-to-no use of additional co-substrate is preferable for the profitability of biogas production. However, while TNI on a unitary basis (per Mg input of m^3 biogas produced) is better, the overall production of biogas is significantly lower, meaning that achieving renewable energy targets would be more difficult. The TNI results are quite sensitive to biogas yield, SB price and transport distances, and thus small deviations could make adding SB a more profitable undertaking. With respect to the economy of scale, medium-to large-scale plants are probably most favourable. This would, however, require significant planning, where many factors (e.g. type and density of farms) would be taken into account and contextualised to local/regional conditions. Planning should make use of dynamic models to be used for optimisation purposes, taking into consideration a number of uncertainties, which could be a key aspect in decision making. Alternative scenarios to be investigated could include a price/value comparison between upgraded biogas to natural gas quality compared to the actual value of biogas used in local CHPs. In fact, biogas injected into the natural gas grid can be used for more diverse purposes and at more valuable times, thanks to storage advantages. In such a scenario, larger biogas plants may have an advantage in connection with the relatively high investment costs involved in upgrading facilities.

4. Conclusions

We carried out an integrated assessment of the biogas production chain based on the co-digestion of pig slurry (PS) and sugar beet pulp silage (SB). The assessment was based on detailed mass, energy and GHG balances, coupled with an evaluation of economic profitability. The influence of feedstock composition was studied using three different feedstocks (i.e. with 0% SB, 12.5%, and 25%). The assessment included three sizes (i.e. 110,000 Mg of biomass per year, 320,000 Mg/year and 500,000 Mg/year) of biogas plant to investigate economies of scale. The study was based ostensibly on experimental data and/or data collected specifically and referring to the Danish context.

We found that increasing the share of SB in the feedstock mix has a beneficial impact on energy and GHG balances. This improvement in energy balances is due mostly to increased biogas and energy production, whereas the transportation of feedstock plays a minor role (regardless of the size of the plant). Utilisation of SB was beneficial for the GHG balance, mainly because of reduced N_2O emissions after applying digestate to land. The results showed that fugitive emissions of CH_4 from the biogas plant may make a significant contribution to overall GHG emissions. The profitability of biogas, on the contrary, was negatively affected by the introduction of SB as a co-substrate, as the increase in income from selling biogas was less than the increase in costs associated with buying SB and the transporting it. The subsidy level was established as a key aspect in biogas profitability.

The size of the biogas plant does not significantly influence the energy and GHG balances, as the performance of the conversion process has little to do with scale. Conversely, though, size is important with regards to economic analysis, as an increase in size is associated with reduced capital costs, which are outweighed by SB-related costs in the PSSB-12.5 and PSSB-25 cases, in particular because of the transportation distances involved.

The results indicate overall that utilising energy crops as a co-substrate, while preferable from an energy and GHG balance point of view, is not profitable from an economic point of view. In this respect, we identified the price of SB and biogas yield as the most sensitive parameters for the results.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2016.06.068.

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Paper B

Review of economic optimisation models of supply chains in the bioenergy industry

Review of economic optimisation models of supply chains in the bioenergy industry

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Abstract

Increased focus on sustainability in the energy sector has led to an increased interest in development of the bioenergy industry, where some of the main challenges are to create profitability with new technologies and seasonal variation of input. The use of mathematical models can assist to ensure the economic viability of bioenergy projects with respect to supply chain design and management. The purpose of this study is to identify and give research directions for solving some of the recent issues faced by the bioenergy industry. This is done through a literature review of existing models within the field of operations research.

The literature shows that research primarily includes parts of the supply chain in the models whereas models including the entire supply chain are still to be developed. Although many elements in the supply chain have been optimised, in general the optimisation of timing and type of end use of the bioenergy has been excluded. Regarding modelling of uncertainty, the bioenergy industry faces a number of uncertainties. These have only been included to a limited extent in existing models. Many models have transportation as end use, especially the models developed in the US. Based on our findings, we suggest that both the upstream and downstream chain should be included in future models including optimisation of the technologies at the end use level to be able to supply the type of fuel that provides the best and most robust solution for the stakeholders.

Keywords: Mathematical modelling; operations research; supply chain optimization; bioenergy; biofuel; biogas.

1 Introduction

Increased awareness of climate change and the desire to use the natural resources more efficiently and sustainable has turned the focus towards the use of biomass as a resource for energy generation. In 2012 the European commission launched the Bio-economy Strategy that addresses the production of renewable biological resources and their conversion into vital products and bioenergy [1]. In December 2015 the European Commission adopted a Circular Economy Package to make the transition from a linear economy where materials and products to a great extent are lost at the end of life of products, towards an economy where waste is seen as a valuable resource as raw materials for new products [2].

The new initiatives regarding bioenergy have led to an increased interest for investing in bioenergy conversion plants. The bioenergy industry is, however, struggling with creating profitable value chains and plants. A bioenergy project has many stakeholders involved, e.g. a number of biomass suppliers and the bioenergy facility investor. The number of stakeholders increases the risk of failure for the project. The cause of the failure most likely has several explanations, e.g. increased competition between bioenergy facility owners for substrate and thereby a lack of stable and cheap input, failure of raising capital for one or more actors, or a general lack of biomasses, see e.g. [3]. Besides the possible lack of biomasses, the stakeholders in the chain are subject to a number of

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difficulties regarding the substrate, as biomasses are deteriorating over time and has limited and variable availability over the year. This means that the bioenergy facilities are subject to an uncertain supply of substrate

The bioenergy industry has been subject to intensive development of new technologies, which has increased the potential numbers of end products that can be produced from biomass. In Denmark, this has resulted in most new biogas plants being interested in upgrading the biogas to natural gas quality instead of the traditional usage in combined heat and power plants [4]. This is also the case in Norway, where Lyng et al. [5] have shown that upgrading and substitution of diesel gives the best results regarding net reduction of GHG-emissions. When new markets are exploited it creates a need for looking at the profitability of the end use markets before deciding on what to invest in. The markets have different structures—some are based in daily or hourly prices, and all markets have some degree of uncertainty in demand and price per energy unit.

The issues raised above have resulted in a number of papers addressing optimization of the supply chain. A supply chain can be defined as the series of processes and activities necessary to produce and deliver a good or a service to the end user or consumer. Optimizing a supply chain will typically consist of defining the structure of the chain to obtain the highest profit for the whole chain, without compromising the need for positive economic results for each actor in the chain. Which parts of the chain is included in the optimization model and the type of optimization will have effects on what kind of results, interpretations, and recommendations that can be given. An example of a supply chain for bioenergy production is shown in Figure 1.1.

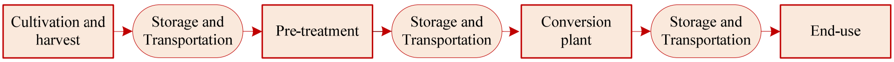

Figure 1.1: An exemplary supply chain with all elements found in the literature

The supply chain in bioenergy production can be seen as two streams: upstream and downstream from the conversion plant. The upstream is the flow of biomass from cultivation/harvest to the plant. The downstream is the flow of bioenergy from the plant to the end use.

We have identified two earlier review papers on bioenergy supply chains exists: [6] and [7]. Both papers identify the main strategic challenges in the supply chains, but only in [7] there is a section describing available mathematical models. We have further identified seven review papers concerning optimization models: [8], [9], [10], [11], [12], [13], and [14]. These papers all give a general review of the existing models and some general research paths for overcoming economic infeasibilities.

To our knowledge, none of the existing review papers give research directions based on the issues in the biogas supply chain raised above. Therefore, the purpose of the review is to identify how modelling of the supply chain has been done in order to capture the mentioned issues: lack of completion, more types of bioenergy end products, and seasonal variability of biomass. We will propose new research paths to address these issues, and this is done through a literature review of existing models with a focus on the field of operations research. We assess which parts of the supply chain are most commonly included in the modelling. Furthermore, the main types of modelling applied are analysed, including the degree to which stochastic programming is applied, and we look into the inclusion of seasonality. As one model can answer many research questions covering e.g. farm land utilisation to size of conversion plants, we will not consider the results of the included models but only what the models include.

2 Method

To cover the relevant literature, we identified the following criteria that the papers have to satisfy to be included in the study:

2

- Operations research models, i.e. the simulation-optimization models are excluded
- The paper must be published in a peer-reviewed journal and in English
- The paper is published up until December 2015 with an emphasis on papers published between 2011 and 2015, i.e. some older papers are included but only to a limited extent

All types of bioenergy are included as several similarities are present for the supply chains.
From former reviews and further search in the on-line database DTU FindIt[2], we found 61 articles satisfying the above criteria, which are included in this review. 12 of these papers are outside the time frame of 2011-2015 but are included because we consider these to be relevant for the background of this review. In Figure 2.1, a network graph of all papers and authors is found. The papers are shown with the large nodes and the authors with small nodes, and an edge between a large and a small node illustrates that the paper is written by the author. The large, black nodes are all the paper included in the review, the blue nodes are the review papers mentioned in the introduction, and the red nodes are papers that have been excluded from the review as other papers describes the same model but the paper still satisfy the criteria defined above. The figure shows that the selection process gives us a good spread of included papers and authors.

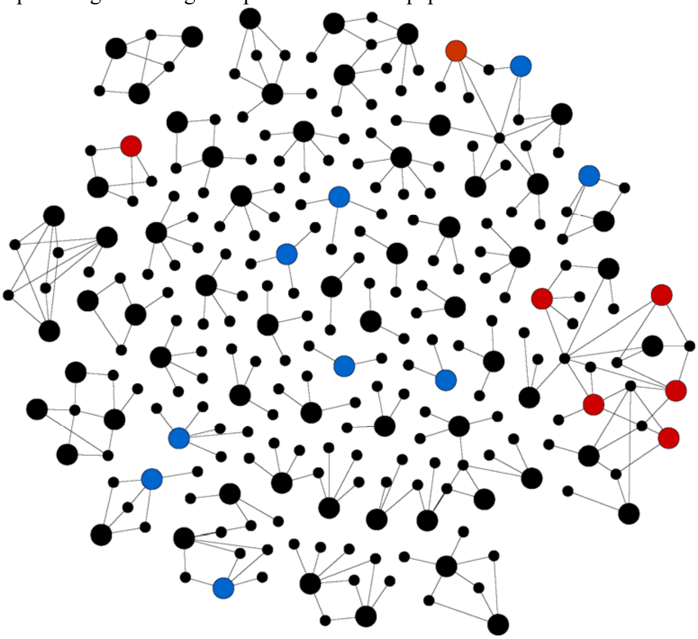

Figure 2.1: Illustration of the spreading of the selected paper in the review (large, black nodes), review papers (blue nodes), excluded papers (red nodes), and all authors (small, black nodes)

We have identified five categories that can be used to classify the papers, to explore the relation between the scope of the models, and the elements included in the supply chain. These are shown in Table 2.1 and discussed below.

[2] The content of DTU FindIt can be seen on: http://api.libguides.com/api_box.php?iid=3935&bid=13937966

Model purpose	Modelling method	Supply chain elements included in the models	Time resolution	Country and end use
Decision levels: strategic, tactical and operational decisions Scope: plant or regional models Decision types: Location decisions, investment decisions	Programming method: LP, MIP, stochastic programming, MINLP Uncertainties included in stochastic programming	Which parts of the supply chain is included in each of the models?	Hourly, weekly, monthly, yearly, no time steps or other	End use category: transport or other in relation to country.

Table 2.1: The categories used in the review

Model purpose: The models are classified into strategic, tactical and operational decisions as done in [10,13]. The strategic approach includes strategic decisions in the chain, e.g. sizing and location of plants, structure of the supply chain, and contracts with producers. The tactical approach reflects the tactical decisions, e.g. an aggregate production plan and inventory management. Finally, in the operational approach the main purpose is to address the day-to-day planning of the supply chain by optimizing the production plan and fulfilling a specific demand. The purpose will be related to other features in the model by dividing them into plant-oriented or regional-based models, and denoting if they contain decisions regarding localization, investments or both.
Modelling method: In [11] it is concluded that mixed integer linear programming (MILP) is the most commonly used modelling technique. In [12] the conclusion is similar, stating that most papers use mixed integer programming methods, usually applied to a specific case study. In this review, the papers are divided into linear programming (LP), mixed-integer programming (MIP), stochastic programming, and mixed-integer non-linear programming (MINLP) models. Further, the uncertainties included are examined.
Supply chain elements included in the models: Different models include different parts of the chain. In [9] and [10] it is concluded that few papers have focused on decisions in both the upstream and downstream part of the chain. This section will show the elements of the supply chains usually included in the models and include a discussion of how to choose elements to include in future models.
Time resolution and seasonal variation: In [13] the models are classified into single-period or multi-period models focusing on the input side and concludes that multi-period models are important to capture seasonality.
Relation between country and end product: With a lot of new technologies available for use of the biomass, it is relevant to see if the country origin of the study has an impact on the type of end product delivered. None of the review papers have looked into the dependence between country and end product. In [11] one conclusion is that bioethanol is the most common end use but the country of the studies is not considered.

3 Results and discussion: Comparison of existing models and suggestions for future models

3.1 Model purpose

The reviewed papers are divided into four main categories based on the decision level: operational-, tactical-, strategic- and integrated decisions. We did not identify any operational decisions models, which are models with a short time scale that can be used to operate the whole chain.
The *plant level* models optimize one conversion plant and its supply chain, where the supply chain is almost equal to the one shown in Figure 3.1. The upstream and downstream sides can have several interconnected chains but there is only one conversion plant in the supply chain. The *regional level* models optimize how to provide a region with its demand of biofuels by deciding on how much a set of conversion plants produce. The regional level models' supply chains can be depicted as in Figure 3.1 where the conversion plants share the same set of producers, storages, pre-treatments, transportation, and end use. The perspective of the plant level and regional level models are typically not the same, as plant level models tend to focus on operating the plants as a private owner and regional level models as part of a larger network of owners.

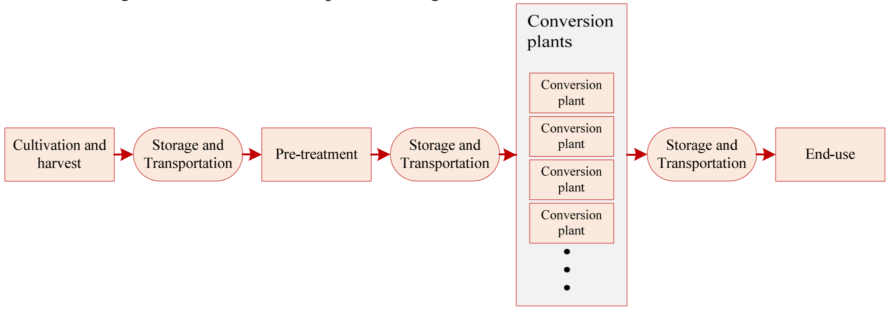

Figure 3.1: Supply chain of regional models

The decision level combined with if the model is on plant or on a regional level can be seen in Figure 3.2[3]. It is seen that most models are strategic or integrated models. Tactical models are more likely to be plant level models. This might be because the plant level models in general can be extended with more details than a regional model because the regional model already includes more details as several plants are operated. This can also explain why a majority of the regional models are purely strategic. In 2015, the tendency was to make strategic, regional models with six new strategic decision models and only one integrated decision model.

[3] A table with all papers and their model focus can be found in Appendix A

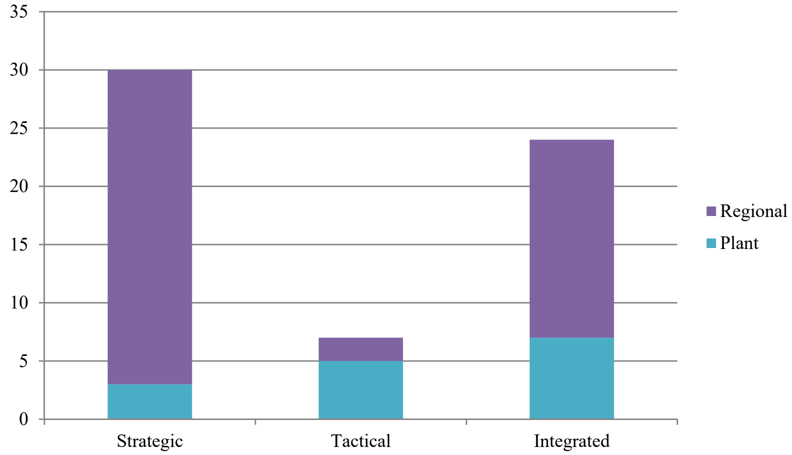

Figure 3.2: Classification on decision level and plant or regional level

Figure 3.3 shows the purpose of the plant level and regional level models. Out of the 61 papers, only 15 of them concern the plant level modelling. The plant level models do only to a limited extent include location of the plant, whereas the regional level models in all cases but five do include analyses of location of plants. This is most likely because planning on plant level is done from a plant owner perspective where the location is given, and the regional level planning is done from a country/municipality perspective with several possible locations. Therefore it would be important to consider the perspective when deciding on whether to use a plant or a regional model.

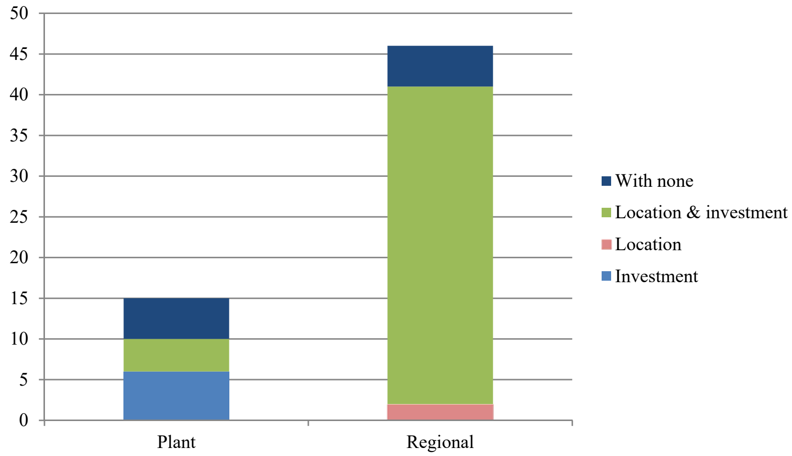

Figure 3.3: The strategic and integrated models are further divided into plant and regional level models combined with what kind of strategic decision are included

Furthermore, it can be seen that only three models of the 54 strategic and integrated models do not include investments. The majority of the regional level models including investment decisions focus on plant capacities and not on different technologies for e.g. the plants or pre-treatments, see for example [15,16].

One should consider the research question when deciding on the presented parts: investment and location; tactical, strategic, or integrated models; and plant level or regional level models. If the aim of a study is e.g. to consider the feasibility of opening a new plant with a given size and a fixed location then an integrated, plant level model which includes investments would be the best choice. In order to capture the biomass seasonality in the modelling, one should use either a tactical or integrated model. To capture the relevance of new technologies, the model needs to be strategic or integrated. To ensure a robust supply chain configuration, an integrated model seems to be the best way to go. One should decide on the path depending on which one—or several—of these issues that should be dealt with.

3.2 Modelling method

From the reviewed papers, the following modelling types are found: linear programming (LP) models, mixed integer programming (MIP) models including one fuzzy programming model, stochastic LP models, stochastic MIP models including two fuzzy programming models with uncertainties, mixed integer non-linear programming (MINLP) models, and two models that were not described mathematically but where an algorithm was applied to solve the problem.

The modelling types can be organised in terms of running time as illustrated in Figure 3.4. In general the more detailed the models are, the more time they take to solve. LP models are the least complicated and have the fastest running time of all the models. The MIP models are slower, but facilitate integer modelling; however, the models may become too simple for real life problems. MINLP models include non-linear elements in the objective function and/or constraints. Even though these models may represent real life better than MIP models, their disadvantage is the long running time.

Algorithms can be used to find reasonable solutions to hard problems fast but the running time of the two models are not discussed in the papers. The two papers using algorithms are not further addressed in this section but are included in all other sections.

Stochastic programming models can handle uncertainties but a higher level of detail result in even longer running times than MIP models. Stochastic LP models are in general faster than stochastic MIP models. In general the solution time of MIP models outperforms the stochastic models and therefore the inclusion of uncertainty should be outweighed with the need for fast running times.

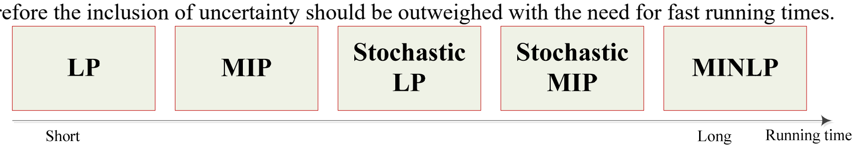

Figure 3.4: General running time for the model types

From Figure 3.5, it can be seen that the models in the examined literature primarily lies within mixed integer programming (MIP). This is mainly because most of the investment models include a decision on predefined sizes. This decision can only be made by integer programming models.

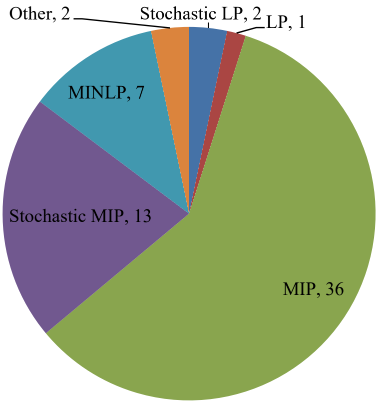

Figure 3.5: Modelling types of the reviewed papers

In recent years, stochastic elements have been included in order of being able to take the uncertainties into account. This can be seen in the reviewed literature as only one stochastic model is from before 2011.

From Table 3.1, the uncertain elements in the stochastic and fuzzy models can be seen. The most dominant element shows to be the feedstock supply uncertainty (10 papers), while the end use demand and end use price is included in eight papers and six papers, respectively. When this table is compared with Table A.1 it shows that four out of the 15 stochastic models are plant level models.

Reference	Available land	Feedstock supply	Feedstock price	Bioenergy yield	End use price	End use demand	Technology evolution
Cundiff et al., 1997 [17]		x					
Dal-Mas et al., 2011 [18]			x		x		
Kim et al., 2011 [19]		x	x	x	x	x	x
Chen and Fan, 2012 [20]		x				x	
Gebreslassie et al., 2012[21]		x				x	
Awudu and Zhang, 2013 [22]					x	x	
Osmani and Zhang, 2013 [23]		x	x		x	x	
Sharma et al., 2013 [24]		x					
Azadeh et al., 2014 [25]					x	x	
Huang et al., 2014 [26]		x					
Osmani and Zhang, 2014 [27]					x		
Shabani et al., 2014 [28]		x					
Tong et al., 2014 [29]		x	x			x	x
Tong et al., 2014 [16]		x				x	x
Balaman and Selim, 2015 [30]	x						

Table 3.1: Elements treated in the stochastic models

Existing models lack the inclusions of stochasticity, which may lead to inaccuracy of results and misleading conclusions. When the last part of the value chain is modelled, one should consider including the stochasticity of end use prices as large variations and uncertainties occur. This is particularly relevant when deciding whether to produce electricity (and heat) or biofuel. One example of this can be seen in Figure 3.6 where the percentage of maximum day-ahead price of electricity in 2014 for Western Denmark (DK1) is plotted based on data from [31], along with the percentage of maximum heat consumption in a Danish district heating network and a polynomial trend-line using a 4^{th} order polynomial for the heat consumption to show the seasonality. The average outdoor temperature in Denmark from 1961-1990, which is the normal period recommended by the World Meteorological Organization, is also plotted. From the figure, it can be seen that the heat consumption depends on the season while the electricity price on average is close to a stable average price for each season, which is the general picture, independent of the year in question. The variation of the electricity price is however large within the seasons and largely unpredictable. Considering this, the electricity price might need to be included as a stochastic element. The variance of the heat consumption shows that seasonality might need to be included in the model as well, but not necessarily as a stochastic component as the fluctuations are largely predictable and depends on the outdoor temperatures. This is further discussed in section 3.4.

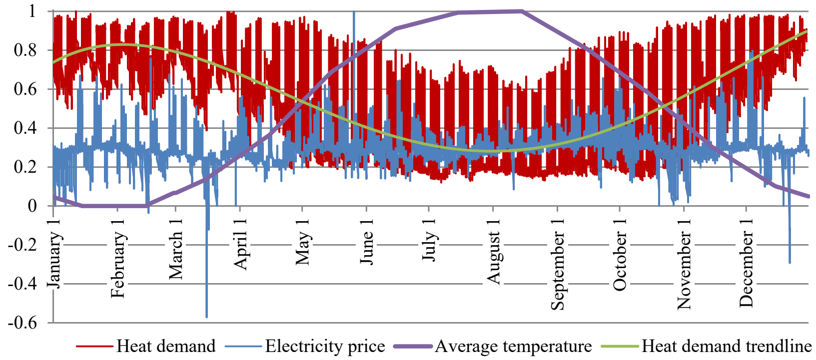

Figure 3.6: Normalised Nord Pool Spot day-ahead prices on electricity in West Denmark from 2014 and a normalised heat demand time series for a medium sized district heating region in Western Denmark from 2001 with a polynomial trend line showing the seasonal variation

Which elements to implement with stochasticity should be considered carefully to avoid unnecessary running time. The fluctuations of the particular element should be studied and whether the element has a large impact on the economy. This could be done by starting with a more detailed, deterministic plant model covering most aspects and finding the most important elements to include in the models. This could for instance be done by a sensitivity analysis as seen in [32].

The inclusion of stochasticity is especially relevant when considering several end products as the uncertainties of one market is different from another, and therefore it will affect which market is evaluated to be the optimal market to operate on.

3.3 Supply chain elements included in the models

An optimization model of a supply chain is restricted by the definition of the supply chain. For each paper, the elements in the chain included in the modelling have been identified as shown in Table 3.2. The papers with the exact same inclusions are grouped, resulting in a total number of combinations of 36, illustrating that there exist a great number of options for modelling the supply chain.

The first element in the chain, included in any of the models, is cultivation. Decisions on cultivation include the decision on how much land to be used for each biomass. After cultivation comes harvest. Decisions on harvest could be on when or where to harvest the biomass. For papers where harvest is not included, the availability of the harvested biomasses is given as input and a price for a unit of biomass is included.

Author	Cultivation	Harvest	Storage	Transport	Pre-treatment	Storage	Transport	Plant	Storage	Transport	End use
Cundiff et al. 1997 [17]		x	x	x				x			
Tembo et al. 2003 [33]	x	x	x	x		x		x			
Celli et al. 2008, Freppaz et al. 2004, Frombo et al. 2009 [34–36]		x		x				x			x
Dunnett et al. 2007 [37]		x			x	x	x	x			
Panichelli and Gnansounou 2008 [38]				x				x		x	
Ekşioğlu et al. 2009 [39]	x	x		x		x		x	x	x	x
Rentizelas et al. 2009, Rentizelas and Tatsiopoulos 2010, Shabani et al. 2014 [28,40,41]				x		x		x			x
Awudu and Zhang 2013, Huang et al. 2010, Marvin et al. 2012, Osmani and Zhang 2014, Paulo et al. 2015, Ren et al. 2015 [22,27,42–46]		x		x				x		x	x
van Dyken et al. 2010 [47]				x	x	x		x			x
An et al. 2011 [48]			x	x	x			x	x	x	x
Ahn et al. 2015, Azadeh et al. 2014, Bai et al. 2011, Cambero et al. 2015, Dal-Mas et al. 2011, Uhlemair et al. 2014 [18,25,49–52]				x				x		x	x
Bowling et al. 2011 [53]				x	x			x			
Kim et al. 2011[19,54]				x	x		x	x		x	x
Papapostolou et al. 2011[55]	x			x				x			x
Machani et al. 2014, Santibañez-Aguilar et al. 2011 [56,57]				x				x			x
Shastri et al. 2011 [58,59]		x	x		x		x	x			
You and Wang 2011 [60]		x	x	x	x	x	x	x	x	x	x
Zhu et al. 2011, Zhu and Yao 2011 [61,62]		x	x	x		x	x	x		x	x
Akgul et al. 2012, Bernardi et al. 2013, Tan et al. 2012 [63–65]	x	x		x				x		x	x
Chen and Fan 2012, Gebreslassie et al. 2012 [20,21]				x				x	x	x	x
Čuček et al. 2012, Osmani and Zhang 2013 [23,66]	x	x		x	x		x	x		x	x
Sultana and Kumar 2012 [15]				x				x			
Walther et al. 2012 [67]		x		x	x		x	x		x	x
Kong et al. 2013, Zhang and Hu 2013 [68,69]		x	x	x	x	x		x	x	x	x
Shabani and Sowlati 2013 [70]				x		x		x			
Bhavna Sharma et al. 2013 [24]	x	x		x		x	x	x			
Zhang et al. 2013 [71]	x	x	x	x	x			x		x	x
Akhtari et al. 2014 [72]		x	x	x	x	x	x	x			x
Huang et al. 2014 [26]				x		x	x	x	x	x	x
Lin et al. 2014 [73]	x	x		x	x	x	x	x		x	x
Marufuzzaman et al. 2014 [74]		x		x				x			
Tong et al. 2014 [16,29]		x		x	x	x	x	x	x	x	x

Balaman and Selim 2015 [30]	x	x		x				x			
De Meyer et al. 2015 [75]	x	x	x	x	x	x	x	x			x
Samsatli et al. 2015 [76]	x	x	x	x	x	x	x	x		x	x
Santibañez-Aguilar et al. 2015 [77]		x	x	x	x	x	x	x		x	x

Table 3.2: The links used in the chain for each paper

The supply chain can include storage at multiple stages. As biomasses are available at different times of year and may decay during storage, storage conditions are highly relevant when optimizing the supply chain. 29 of the papers include storage at one or more points in the chain. When storage is included, there is a probability of loss of mass and energy content from the storage depending on the type of storage and biomass. The mass loss is included by using a deterioration rate for all the papers that include storage loss. However, none of the papers include loss of energy content in the biomass. To address the issue of seasonality and degradation of biomasses, we suggest to include storages and adding both mass and energy losses in the chain. The importance of including mass losses can be seen when looking at e.g. ensilage of sugar beets. In [78], the mass loss after ensilage of sugar beet for 18 months was 85%. For the energy, according to [79] an increase in biogas yield when ensiling the sugar beet of 2% per week over a 26 week period. This would increase the biogas yield of the sugar beet with 167% over the 26 weeks.

Transportation is also included in several parts of the chain. This is done either by modelling it explicitly, i.e. a more or less detailed plan of transportation, or by using a cost for transportation of the products. The decision on how to include transportation will have an effect on the running time of the model. Therefore, whether or not to include transportation explicitly should be decided based on an evaluation of the expected gain or loss considering also the decision level of the model. A good approximation of the costs can in some cases represent the transportation in a sufficient way.

Only 21 of the papers include pre-treatment of the biomasses explicitly in the model. Decisions on pre-treatment are typically on the type of pre-treatment for each biomass or location of the pre-treatment. Pre-treatment is relevant in terms of better usage of biomasses, for lowering transportation costs etc.

Examples of decisions on the conversion plant are which input mix to use at each time period or what size of plant to install. The typical way of including the size is to include different capacities which the model can choose from, but some papers, e.g. [34], includes the size as a linear variable which will give the model freedom to choose the optimal size, but does not reflect economy of scale.

11 papers end their supply chain at the conversion plant. This means that no optimization is done with regard to type of end use, timing of production, or transport/transmission of the end-product. No general way of including end use can be seen, resulting in several ways of handling the optimization problem. One problem is to deliver a certain energy demand to a region, and a constraint on the problem will, thereby, become a demand constraint. Another problem frequently occurring in the papers is the number and sizes of the end use plants, e.g. CHP plants. As described further in section 3.5, decision on types of end use can also become an optimization problem. This, however, has only been addressed by [57], [52], and [76], which are all strategic models. The choice of end use is an issue when considering the recent interest in flexible multi-generation plants [80] and should be considered to exploit the benefits of being able to operate on different end markets also in tactical or integrated models.

The many setups of the chain underline the necessity of evaluating the relevance of each element of the chain before making the optimization model. When considering the issue of profitability, the evaluation should focus on the share of economy that the element has, as well as the choices which can be affected by the decision maker. This share will show how many of the following decisions should be included in the optimization: scale (investment), timing, type, and location. Furthermore, one must decide which restrictions apply to the model. These restrictions could be losses during storage and whether e.g. a heat demand must be fulfilled.

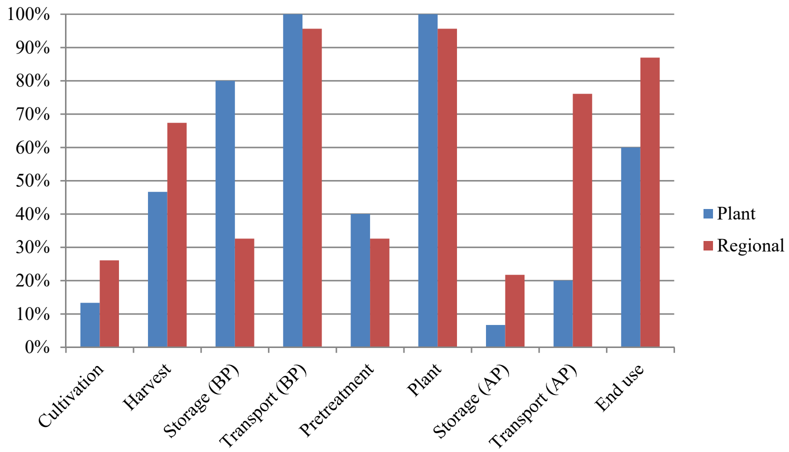

Figure 3.7: Elements included in plant and regional models. BP and AP denote before and after plant.

The relation between the elements included and whether the models are plant or regional models can be seen in Figure 3.7. Here the storage and transportation options before the plant are combined into one storage and one transportation option. The figure shows that the regional models are more likely to include cultivation and harvest. This is likely to be because of where the owner of the system has an impact. One plant owner can not affect the decision on where and when to harvest but an owner with several plants has the possibility both to own the land and impact the decisions of when and where to harvest. For storage before the plant and the pre-treatment, the plant level models are better represented. The downstream part of the chain shows to be better represented in the regional models. Again, this might be because a regional plant owner will have a better control of the downstream chain. Including end use in a plant level model would however make it possible to optimize the design of a plant for different possible end uses.

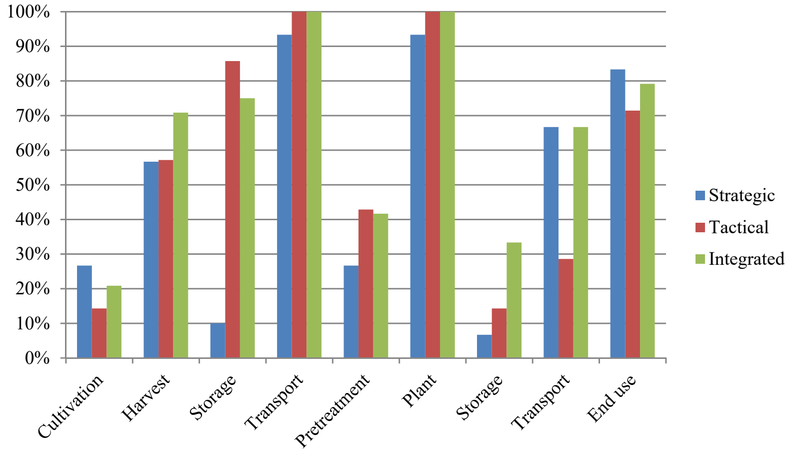

Figure 3.8: Elements divided on the type of model: strategic, tactical or integrated

In Figure 3.8 the elements are divided on the three types of models, i.e. strategic, tactical, and integrated decision models. The main differences are again on the storage and pre-treatment where the tactical and integrated models have a much higher representation than the strategic models. Regarding storage, this makes sense as how much to store in each time step is a tactical decision and not a strategic one. However, inclusion of the investment in storages is also relevant in strategic models. The pre-treatment of the biomasses could be relevant for all types of models and is also linked to the issue of storage.

For strategic and integrated models we recommend to include the possibility to choose from different types of storages, pre-treatment, conversion plants, and end use, if these elements show to have a significant impact on the overall economy. For the tactical models, we suggest to include as many details as possible, as these models in general have a shorter time period and therefore can handle more decisions. The amount of details to be included should be weighed against the wish to include stochastic elements in the modelling. If the decision-maker has an influence on specific elements of the chain, we recommend including it whenever possible.

3.4 *Time resolution and seasonal variation*

Depending on what the model is applied for, it is relevant to look at time resolution as a way to determine the optimal handling of the supply chain over time. If the model is to include end use, the time resolution is highly relevant as energy prices in most cases change on an hourly or daily basis. On the other hand, monthly or weekly time steps are relevant for agriculture and heat production as seasonal variation can be captured on this time scale. As seen in Figure 3.9, the papers mainly fall into two categories: no time steps or monthly time steps. The little investigation in hourly time resolution underlines the fact that end use optimization can be further explored as end use prices may be relevant on an hourly basis, particularly if electricity is one of the possible end products as described in Section 3.2. We believe that especially for end use oriented models, time steps are important as energy prices in many cases vary on an hourly or daily basis.

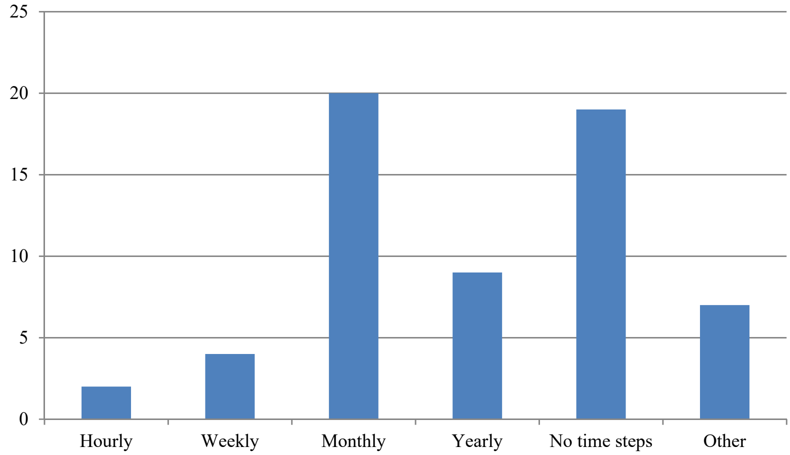

Figure 3.9: The use of time resolution in the models

An advantage of including time steps is that seasonal variation of the input can be taken into account. A typical bioenergy plant will use biomasses with seasonal variation, e.g. corn and grass. Therefore, a variation of the availability is important to include, requiring a model with time steps shorter than a year. As most of the models include a constraint specifying how much biomass is available, this could be specified over time to reflect the seasonal variation. This would also allow taking decay during storage into account. The length of the time steps must be decided depending on the type of biomasses used and their fluctuation in availability during the season, as well as fluctuations in other parts of the chain, e.g. at the demand side. 30 of the papers include seasonal variation. The seasonal variation in biomass input should be included in the models to resemble real life as well as possible.
Combining the seasonal variation of biomasses with the need of short time steps for energy price fluctuations, one solution is to use hourly time steps. This will, in most cases, result in the model size being too big to solve within a reasonable time frame, but this can be overcome by dividing the problem into two parts, upstream and downstream of the plant, and then letting the time resolution be weekly or monthly upstream and hourly or daily downstream as done in the model from [79].

3.5 Relation between country and end use

As different countries have different structures of their energy systems, it is apparent that the end use of the bioenergy modelled must depend on the country of the study. The country of the study is shown in Table 3.3.

	USA	Canada	Europe	Other countries	Total
Only transport	26	0	6	4	**36**
One other end use	2	3	4	1	**10**
More than one end use	1	3	10	1	**15**
Total	29	6	20	6	**61**

Table 3.3: The origin of the papers combined with the end use

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Here, it can also be seen that the main contributor to the literature within bioenergy supply chain optimization is the US. It is evident that the end use in US is transportation fuels, whereas, only 10 of the non-US papers have this focus. Furthermore, all six of the articles from Canada are either not having transport as end use or are not including transport as the only end use.
Looking at USA and Canada, there seem to be different needs of the bioenergy as the Canadian papers use the bioenergy for heat or electricity. The choice of end use might imply that for the US, the use of bioenergy for heat or electricity is subject to a higher degree of competition from other fuels, whereas the opposite might be true for bioenergy in the transportation sector in Canada.
The papers from other countries do not show a clear tendency towards any of the technologies, but the mixed scope of the papers indicates that the relevance of looking at what type of end use could be satisfied by bioenergy is larger in these countries. 15 of the paper includes more than one end use but as already mentioned, only three papers optimize the usage of the bioenergy. This can, however, affect the optimal solution, as different end use opportunities will give different economic results. An example of a bioenergy type with many opportunities is biogas, where the possible uses are e.g. combined heat and power plants, injection to natural gas grids, or use as transport fuel.

4 Conclusion

Based on the issues of economic viability, a variety of end products, and seasonality and degradation of biomasses, we have made a systematic literature review of present papers describing mathematical optimization models to see how these issues are treated. 61 papers were reviewed and classified according to the five sections: 1) model purpose; 2) modelling type; 3) supply chain elements included in the model; 4) time aggregation and seasonal variation; and 5) geography and end use.
The study shows that most work has been done in the strategic and strategic/tactical integrated decision models. Most models are MIP models but we see a recent trend towards more stochastic models. Few studies include the whole chain in their models and the optimization on the downstream part of the chain is limited. Most models are monthly models and include seasonal variation on biomasses, however, the seasonality of end product prices are in most models not included. Last, we find a connection between the country of the study and the end use.
If one is to look at the economic viability, we suggest carefully considering the amount of detail needed for each of the elements in the supply chain; First, for each element in the chain it should be considered whether to include optimization of: scale, location, type, and timing. Second, important restrictions should be addressed: are there any significant losses during storage, is there a specific energy demand to cover, etc. Whether to include these elements should be evaluated based on an evaluation of the share of economy for each part and whether an inclusion of the element will result in a representation that will change the solution.
For ensuring the economic viability, the possible end products and their markets must also be considered. Our review shows that the type of end-product in many cases is not included as part of the optimization but decided beforehand. We suggest that both the technologies of the bioenergy plant as well as the downstream part of the chain are included in the model to increase the profitability of the bioenergy supply chain.
Both for considering the end products and the seasonality of the biomasses, it might be relevant to include stochasticity. As an inclusion increases the running time of the models significantly, we suggest deciding on which of the possible uncertainties to include in the following way; First, the uncertainties of each element in the chain must be described. Second, the variations that can occur due to the uncertainties must be evaluated. Last, the impact on economy of these uncertainties must be evaluated. Based on these steps, a decision can be made on which uncertainties to include.

The above recommendations increase the model size, so to limit the size and include as many features as possible, we suggest a two-part model which is divided at the bioenergy plant. This model can have one time resolution on the upstream part and a smaller time resolution on the downstream part of the chain. The time resolutions should be considered—again by looking at the impact on economy when adding details to the model.

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Appendix A

	Plant		Regional	
Strategic	Chen and Fan 2012	[20]	Freppaz et al. 2004	[34]
	Machani et al. 2014	[57]	Celli et al. 2008	[35]
	Uhlemair et al. 2014	[50]	Panichelli and Gnansounou 2008	[38]
			Frombo et al. 2009	[36]
			Huang et al. 2010	[42]
			An et al. 2011b	[48]
			Bowling et al. 2011	[53]
			Kim et al. 2011	[19]
			Kim et al. 2011	[54]
			Papapostolou et al. 2011	[55]
			Santibañez-Aguilar et al. 2011	[56]
			Akgul et al. 2012	[81]
			Čuček et al. 2012	[66]
			Marvin et al. 2012	[44]
			Marvin et al. 2012	[43]
			Sultana and Kumar 2012	[15]
			Tan et al. 2012	[64]
			Walther et al. 2012	[67]
			Bernardi et al. 2013	[65]
			Osmani and Zhang 2013	[23]
			Marufuzzaman et al. 2014	[74]
			Ahn et al. 2015	[51]
			Cambero et al. 2015	[52]
			De Meyer et al. 2015	[75]
			Paulo et al. 2015	[45]
			Ren et al. 2015	[46]
			Samsatli et al. 2015	[76]
Tactical	van Dyken et al. 2010	[47]	Awudu and Zhang 2013	[22]
	Shabani and Sowlati 2013	[70]	Kong et al. 2013	[68]
	Bhavna Sharma et al. 2013	[24]		
	Akhtari et al. 2014	[72]		
	Shabani et al. 2014	[28]		
Integrated	Cundiff et al. 1997	[17]	Tembo et al. 2003	[33]
	Dunnett et al. 2007	[37]	Ekşioğlu et al. 2009	[39]
	Rentizelas et al. 2009	[40]	Bai et al. 2011	[49]
	Rentizelas and Tatsiopoulos 2010	[41]	Dal-Mas et al. 2011	[18]
	Shastri et al. 2011	[58]	You and Wang 2011	[60]
	Shastri et al. 2011	[59]	Zhu et al. 2011	[61]
	Lin et al. 2014	[73]	Zhu and Yao 2011	[62]
			Gebreslassie et al. 2012	[21]
			Zhang et al. 2013	[71]
			Zhang and Hu 2013	[69]
			Azadeh et al. 2014	[25]
			Huang et al. 2014	[26]
			Osmani and Zhang 2014	[27]
			Tong et al. 2014	[16]
			Tong et al. 2014	[29]
			Balaman and Selim 2015	[30]
			Santibañez-Aguilar et al. 2015	[77]

Table A.1: Classification on decision level and plant or regional level

Paper C

Optimizing the supply chain of biomass and biogas for a single plant considering mass and energy losses

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Innovative Applications of O.R.

Optimizing the supply chain of biomass and biogas for a single plant considering mass and energy losses

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A B S T R A C T

The share of renewable energy in the Danish energy sector is increasing and the goal is that biogas production should reach a production level of 17 petajoules (PJ) in 2020 according to the Danish Energy Agency. However, this goal is currently not reachable due to lack of investments in biogas plants.

In this paper, a mixed integer programming (MIP) model for finding the optimal production and investment plan for a biogas supply chain is presented to ensure better economy for the full chain hopefully stimulating future investments in biogas. The model makes use of step-wise linear functions to represent capital and operational expenditures at the biogas plant; considers the chain from the farmer to the end market; and includes changes of mass and energy content along the chain by modeling the losses and gains for all processes in the chain. Biomass inputs are scheduled on a weekly basis whereas energy outputs are scheduled on an hourly basis to better capture the changes of energy prices and potentially take advantage of these changes.

The model is tested on a case study with co-digestion of straw, sugar beet and manure, considering natural gas, heat, and electricity as end products. The model finds a production and investment plan for a predefined location of the plant within half an hour of central processing unit (CPU) time. The resulting project turns out to be profitable and gives a production plan for each process, which underlines the possibilities of optimizing the processes in a biogas project.

1. Introduction

The Danish government has set an ambitious goal of having a biogas production level of 17 petajoules in 2020 (Danish Energy Agency, 2012a). This goal has turned out to be hard to reach because of the lack of willingness to invest in new biogas plants. An overview of planned investments from the Danish Energy Agency shows that the goal cannot be reached even when including proposed projects which are assessed to be unlikely to go ahead (Danish Energy Agency, 2014b). Therefore, in order to stimulate future investments in biogas plants a tool for designing the optimal supply chain, size of processes, and input types to use is developed.

Denmark has a biomass potential of around 200 petajoules and in order to fulfill the Danish goal of becoming independent of fossil fuel by 2050, it will be necessary to harvest this potential and utilize it optimally, thereby avoiding a potentially unsustainable level of biomass import. A high share of the available biomass, around 80%, is in the shape of waste fractions from agriculture and forestry (Danish Energy Agency, 2014a). The two main waste fractions, each constituting around 40% of the waste fractions from agriculture and forestry, are manure and straw (Danish Energy Agency, 2014a). Manure can be used for biogas production, thereby creating the double benefit of producing energy and reducing emissions from spreading raw manure on fields as the digestate resulting from the anaerobic digestion has less emissions compared to manure (Wenzel et al., 2014). Manure, however, has a low biogas yield on its own, so typically additional biomass inputs are needed for co-digestion to ensure economic feasibility of biogas plants. Currently, only 5% of the manure potential is utilized (Danish Energy Agency, 2014a). After pretreatment, straw can be used as additional biomass to increase the biogas yield. Less than half of the straw potential is currently utilized for energy production, while the rest is plowed down or used as deep litter. Another possibility is to grow energy crops, such as sugar beet, which grows well in Denmark. In this article the options of adding sugar beet and straw to manure for co-digestion are evaluated.

The literature dealing with optimization of supply chains for biofuels has been studied in several literature papers (An, Wilhelm, & Searcy, 2011; Ba, Prins, & Prodhon, 2016; De Meyer, Cattrysse, Rasinmäki, & Van Orshoven, 2014; Iakovou, Karagiannidis, Vlachos, Toka, & Malamakis, 2010; Sharma, Ingalls, Jones, & Khanchi, 2013).

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The literature can be split into two main focus areas: models focused on optimization of the supply chains for one plant (Akhtari, Sowlati, & Day, 2014; Chen & Fan, 2012; Shabani & Sowlati, 2013), and models focused on optimization of the supply chain in a region with multiple plants (De Meyer, Cattrysse, & Van Orshoven, 2015; Ekşioğlu, Acharya, Leightley, & Arora, 2009; Huang, Chen, & Fan, 2010).

Only few papers include a decision on output energy mode, e.g. Börjesson and Ahlgren (2012), or the timing of storages for obtaining the best price of energy or satisfying a specific demand, e.g. Huang, Fan, and Chen (2014). However, to our knowledge there are no papers addressing the optimal sizing of heat and biogas storages as well as output energy mode although optimal timing of production can lead to a higher income on the output side making plants more economically viable. Several articles concern modeling the supply of biomass to a bioenergy plant, e.g. Eriksson and Björheden (1989), Shabani and Sowlati (2013) and Zhang, Osmani, Awudu, and Gonela (2013) but only in the article by Van Dyken, Bakken, and Skjelbred (2010) the losses in the energy value of the product are included. Furthermore of the papers reviewed, most papers include sizing of the plants as integer decisions (Gebreslassie, Yao, & You, 2012; Kim, Realff, & Lee, 2011).

The objective of this study is to model the supply chain of biogas production, where the supply chain is defined from farmer to the end market, in this case the heat, electricity and natural gas markets. The natural gas market is the natural gas grid, which can be utilized by upgrading biogas to biomethane. The modeling is done by finding the optimal flow of biomasses and biogas through a number of processes and deciding on which processes to invest in for a predefined location of the biogas plant. Furthermore, the model includes both the mass loss and the energy loss throughout the chain as well as a simple transport model.

The model seeks to find the optimal way of producing biogas such that the biogas plant projects become economically feasible by maximizing the profit. This will support the goal of producing more biogas in Denmark. The model can be used for evaluating different support schemes and their impact on the production of biogas. Moreover, the fairness of costs and required prices for each stakeholder can be evaluated as the prices of biomass and end products are decided between the stakeholders. An unfair distribution of profit, e.g. one stakeholder not earning anything, would not result in a biogas project. Last, the model can be used on existing facilities to optimally plan the production when used with exogenously given plant capacities. The stakeholder extension and the production planning will not been further addressed in this paper.

The paper is organized as follows: In the following Section 2 we give an overview of the value chain at the biogas plant, and introduce a network formulation of the problem. The model makes use of a time-place network on the output side, and a time-place-energy network on the input side. In Section 3 we use the constructed network to state the objective function of the problem and define constraints on the input and output side. Moreover, we model the transportation costs of collecting manure or crops as a number of concentric circles around the plant. Finally, in Section 4 we use the developed model to analyze the construction of a specific plant in Denmark, and discuss the results in Section 5. The paper is briefly concluded in Section 6 and future challenges are discussed.

2. Problem statement

The biogas supply chain is defined as the processes from farmer to energy demand. Fig. 1 gives an overview of the supply chain used in the model. Manure or other biomass types, e.g. crops, waste or waste water, are the input to the model. Each arrow illustrates transport of either biomass, biogas or digestate. The inputs can go through storage—denoted by the small circles—pretreatment and storage again before arriving to the biogas plant. Here the anaerobic digestion takes place and the result is biogas and digestate. The digestate can go to a storage facility and then back to the livestock keepers or be sold elsewhere. The biogas goes through biogas storage and can from here either be: upgraded through water scrubbing, organic physical scrubbing, pressure swing absorption, or chemical scrubbing and sold as biomethane on the natural gas grid; upgraded through chemical methanation, where hydrogen is added to the biogas, and be sold on the natural gas grid and as heat; used in a boiler for heat production; or be used directly for combined heat-and-power (CHP) production, see also Section 4. The problem is to find the optimal way through the supply chain from the farmer to the energy demand, e.g. deciding how much of each input should be applied depending on transportation costs etc., what pretreatment type should be used, what type of energy the biogas should be used for etc. The planning horizon is one year and investment costs have been annualized.

The model uses different time scales on the input and output side. This is due to the fact that electricity prices vary on an hourly basis whereas biomass input is neither possible nor relevant to estimate on such a short time scale. To capture the seasonal variation of the biomasses, the input side is on a weekly basis, meaning that the available amount is registered for each week of the year.

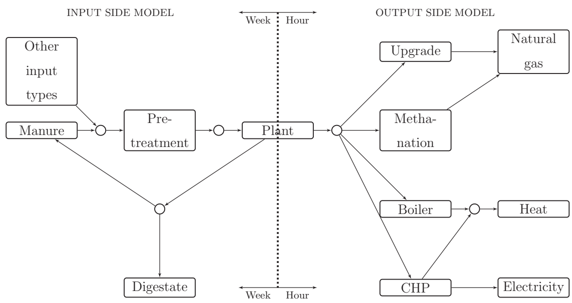

Fig. 1. The biogas value chain from farmer to energy demand with the input side using a weekly time scale and the output side using an hourly time scale.

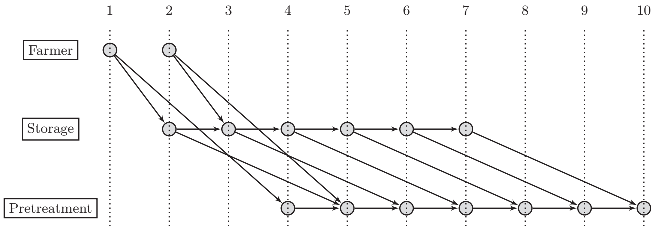

Fig. 2. Example of a network in a (time,process)-space where the time periods are shown in the top and the process names on the left. The arcs going from vertex (time 1, farmer) to (time 2, storage) are possible routes for the biomass to take from the farmer to a storage facility.

On the input side, the model must keep track of both the mass and the energy content of the input. The mass is needed for sizing of the processes and amount of digestate, while the energy content must be used for calculating the biogas yield for the output side. Biomass can lose energy content as well as mass because of degradation of the biomass. For some processes the energy content might increase because of an increased digestability while the mass changes at another rate. On the output side, it is on the other hand only necessary to keep track of the amount of cubic meter biogas available as the heating value is assumed constant.

The supply chain is specified for the input and output side. Each side can be explained by using a number of processes $\mathcal{P}$ and $\overline{\mathcal{P}}$, and over the set of time periods $\mathcal{T}$ and $\overline{\mathcal{T}}$, where an overline is for the sets on the output side. Further, the input side uses the energy content $\mathcal{E}$ of each input type $\mathcal{I}$. All nomenclature is given in Appendix A.

2.1. Network formulation

The problem is solved using a network flow model in a (time, process, energy content)-space on the input side and in a (time, process)-space on the output side. A small example of a (time, process)-space graph is shown in Fig. 2.

The graph on the input side, $\mathcal{G}(\mathcal{V}, \mathcal{A})$, is therefore described by the vertex set $\mathcal{V}$ and the arc set $\mathcal{A}$. An input side vertex $v \in \mathcal{V}$ is defined as the tuple $v = (i, p, t, e) \in (\mathcal{I} \times \mathcal{P} \times \mathcal{T} \times \mathcal{E})$.

On the output side, the graph, $\mathcal{G}(\overline{\mathcal{V}}, \overline{\mathcal{A}})$, is described by the vertex set $\overline{\mathcal{V}}$ and the arc set $\overline{\mathcal{A}}$. Last, the output side vertex $v \in \overline{\mathcal{V}}$ is defined as the tuple $v = (p, t) \in (\overline{\mathcal{P}} \times \overline{\mathcal{T}})$.

The definition of processes can be extended to include the placement in the chain. The farmers are in the process set $\mathcal{P}^F$. The plant on the input side are in the process set $\mathcal{P}^P$, and on the output side in $\overline{\mathcal{P}}^P$. Natural gas, heat and electricity are in the process set $\overline{\mathcal{P}}^E$. Between the farmers and the plant on the input side are the inner processes contained in the set $\mathcal{P}^I$. On the output side the inner processes, $\overline{\mathcal{P}}^I$, are between the plant and the end use. The used superscripts are also used for the vertices for the processes.

For the arcs a in the network, $\mathcal{A}^-(v)$ and $\mathcal{A}^+(v)$ are the input arcs arriving at vertex v and leaving vertex v, respectively. The +/- and v can be left out to state any arcs on the input side. Further, $\mathcal{A}(v', v)$ represents all arcs between vertex v' and vertex v. Equivalent sets are defined on the output side by adding an overline on $\mathcal{A}$.

Using this graph representation, the resulting problem is a variation of a *minimum cost flow problem with node capacities* (Ahuja, Magnanti, & Orlin, 1993). For the input side, it is also a multi-commodity flow problem but this is handled by only generating arcs for the relevant biomasses, such that each biomass type has its

3. Mathematical formulation

The model formulation is formulated based on the constructed network and is given in the following sections.

3.1. Objective function

The objective of the model is to maximize profit while satisfying the constraints described below. In the objective function the following variables are used. The flow on an arc $a \in \mathcal{A}$ and $a \in \overline{\mathcal{A}}$ is given by the variables x_a and $\overline{x}_a$ for the input side and output side, respectively. The variable $x^{left}_{p,t}$ describes the amount of energy that cannot be sold due to a lack of demand from process p in time t. This amount is explained further in Section 3.4. The capacity of a process p for input type i is given by $k_{i,\,p}$ and $\overline{k}_p$.

For the biogas plant, economy of scale is modeled by making the cost curves for OPEX and CAPEX into piece-wise linear functions. The set of breakpoints between each linear segment is denoted $\mathcal{N}$. The variables, x^{SOS2}_n and k^{SOS2}_n, describe the flow into the plant and the capacity of the plant. These are both special ordered set 2 (SOS2) variables and can obtain values between 0 and 1, where at most two consecutive variables can obtain a non-zero value. The non-zero variables describe where the optimal solution is found on the linear segment between them (Beale & Tomlin, 1970).

The transportation cost curve, described in Section 3.5, is a piece-wise linear function and consists of a set of segments $\mathcal{M}$. The variable $x^{trans}_{i,m}$ describes the flow of each input type i transported on each segment $m \in \mathcal{M}$ of the transportation cost curve. The variable $x^{trans,xdig}_m$ is the amount of extra digestate that must be transported to farmers not delivering manure.

The objective function can be formulated as:

$$\max \sum_{v \in \mathcal{V}^P} \sum_{a \in \mathcal{A}^-(v)} x_a \, \eta^{plant} \, \rho^{dig} \tag{1a}$$

$$+ \sum_{\substack{v=(p,t)\in \\ \overline{\mathcal{V}}^E \cap (\overline{\mathcal{P}}^E \times \overline{\mathcal{T}})}} \sum_{a \in \overline{\mathcal{A}}^-(v)} (\overline{x}_a \, \rho^{support}_p + \overline{x}_a \, \overline{\rho}_{p,t} \, \eta^{available}) \tag{1b}$$

$$- \sum_{p \in \overline{\mathcal{P}}} \sum_{t \in \overline{\mathcal{T}}} x^{left}_{p,t} \, \overline{\rho}_{p,t} \, \eta^{available} \tag{1c}$$

$$- \sum_{\substack{v=(i,p,t,e)\in \\ \mathcal{V}^F \cap (\mathcal{I} \times \mathcal{P}^F \times \mathcal{T} \times \mathcal{E})}} \sum_{a \in \mathcal{A}^+(v)} x_a \, c^{prod}_i \tag{1d}$$

$$- \sum_{v=(i,p,t,e)\in} \sum_{a \in \mathcal{A}^-(v)} x_a \, (c^{OPEX}_{i,p} + c^{OPEX,var}_{i,p,t}) \tag{1e}$$

$$- \sum_{\substack{v=(p,t)\in \\ \bar{\mathcal{V}}\cap(\bar{\mathcal{P}}\times\bar{\mathcal{T}})}} \sum_{a\in\bar{\mathcal{A}}^-(v)} \bar{x}_a \bar{c}_p^{OPEX} \tag{1f}$$

$$- \sum_{i\in\mathcal{I}} \sum_{p\in\mathcal{P}} k_{i,p} \frac{T}{t_{i,p}^{min}} c_{i,p}^{CAPEX} - \sum_{p\in\bar{\mathcal{P}}} \bar{k}_p \bar{c}_p^{CAPEX} \tag{1g}$$

$$- \sum_{n\in\mathcal{N}} x_n^{SOS2} c_n^{OPEX,SOS2} - \sum_{n\in\mathcal{N}} k_n^{SOS2} c_n^{CAPEX,SOS2} \tag{1h}$$

$$- \sum_{i\in\mathcal{I}} \sum_{m\in\mathcal{M}} x_{i,m}^{trans} c_{i,m}^{TRANS} - \sum_{m\in\mathcal{M}} x_m^{trans,xdig} c_m^{TRANS,xdig} \tag{1i}$$

$$- \sum_{v\in\mathcal{V}^P} \sum_{a\in\mathcal{A}^-(v)} x_a \eta^{plant} c^{HANDLING,dig} \tag{1j}$$

Expressions (1a)–(1c) give the income which comes from selling digestate and biogas, and support for producing upgraded biogas, where ρ^{dig}, $\bar{\rho}_{p,t}$, and $\rho_p^{support}$ are prices and support obtained, η^{plant} represents the percentage of mass left after mass loss in the biogas plant, and $\eta^{available}$ is the percentage of biogas that is not flared. This percentage is fixed and represents the anticipated amount that must be flared due to operational or maintenance reasons. $x_{p,t}^{left}$ is deducted from the flow to reflect what can be sold. The remaining expressions are the costs: (1d) is the cost of buying biomass, (1e)–(1g) are the operational expenditures (OPEX) and capital expenditures (CAPEX) on the input and output side, (1h) is the OPEX and CAPEX for the biogas plant, and (1i) and (1j) are the transportation and handling costs of biomass and digestate. The costs for each of these equations are given by the parameters: c_i^{prod} is the production cost of input type i; $c_{i,p}^{OPEX}$ and $\bar{c}_p^{OPEX}$ are the OPEX of input and output processes; $c_{i,p}^{CAPEX}$ and $\bar{c}_p^{CAPEX}$ are the CAPEX of input and output processes; $c_n^{OPEX,SOS2}$ and $c_n^{CAPEX,SOS2}$ are OPEX and CAPEX of the biogas plant in each breakpoint n; $c_{i,m}^{trans}$ and $c_m^{TRANS,xdig}$ are the transportation cost of biomasses and digestate; and $c^{HANDLING,dig}$ is the loading/unloading cost of digestate. As CAPEX for the input processes is given on an annual basis (tonnes/year), the capacity has to be scaled to match this. This is done by multiplying with the length of the year in weeks T and divide by the minimum process time $t_{i,p}^{min}$ because the capacity is based on the required process time. An example is the biogas plant, where a capacity of 5769 tonnes with a minimum process time of three weeks is the same as a capacity of 100,000 tonnes/year.

3.2. Constraints on the input and output side

Both the input and the output side share the same type of constraints. For simplicity, the same type of constraints are only shown for the input side sets but the full model can be seen in Appendix B and nomenclature in Appendix A. The constraints are:

$$\sum_{\substack{v'=(i',p',t',e')\in \\ \mathcal{V}\cap(\mathcal{I}\times\mathcal{P}\times\mathcal{T}\times\mathcal{E})}} \sum_{a\in\mathcal{A}(v',v)} x_a \eta_{i,p',p} = \sum_{a\in\mathcal{A}^+(v)} x_a$$
$$\forall v = (i,p,t,e) \in \mathcal{V}^I \cap (\mathcal{I}\times\mathcal{P}^I\times\mathcal{T}\times\mathcal{E}) \tag{2}$$

$$\sum_{\substack{v'=(i,p',t',e')\in \\ \mathcal{V}\cap(\mathcal{P}\times\mathcal{T}\times\mathcal{E})|p\neq p'}} \sum_{a\in\mathcal{A}(v',v)} x_a \eta_{i,p',p} \le \sum_{\substack{v''=(i,p'',t'',e'')\in \\ \mathcal{V}\cap(\mathcal{P}\times\mathcal{T}\times\mathcal{E})|p\neq p''}} \sum_{a\in\mathcal{A}_{proc}(v,v'')} \frac{x_a}{(\eta_{i,p,p})^{t''-t}}$$
$$\forall v = (i,p,t,e) \in \mathcal{V}^I \cap (\mathcal{I}\times\mathcal{P}^I\times\mathcal{T}\times\mathcal{E}) \tag{3}$$

$$\sum_{v=(i,p,t,e)\in\mathcal{V}\cap\mathcal{E}} \sum_{a\in\mathcal{A}^-(v)} x_a + \sum_{v=(i,p,t,e)\in\mathcal{V}\cap\mathcal{E}} \sum_{a\in\mathcal{A}_{cap}^-(v)} x_a \le k_{i,p}$$
$$\forall (i,p,t) \in \mathcal{I}\times\mathcal{P}\times\mathcal{T} \tag{4}$$

Constraint (2) ensures flow conservation in all processes where $\eta_{i,p',p}$ is the percentage of mass left after process p.

In order to solve the problem of minimum process time, the (time, process, energy content)-graph for the input side and the (time, process)-graph for the output side are constructed such that the arrival time in a process includes the minimum process time of the process. The related constraint is (3), where a constraint is written for each vertex not being the first or last in the chain. The left hand side represents the flow to the vertex including the mass loss. The right hand side includes all arcs that leave the process within the given maximum process time, $\mathcal{A}_{proc}(v, v'')$, with a loss of energy, and the division by $(\eta_{i,p,p})^{t''-t}$ represents the percentage of mass left in time t''. In Fig. 3, an example of the process arcs are shown. The red arc, corresponding to the set $\mathcal{A}(v', v)$, describes the flow to the process with a minimum process time of 1 week—the minimum process time is included in the arrival time of the red arc—and a maximum process time of 5 weeks. The blue arcs indicate that the input in time period 3 must leave the process again before time period 7, corresponding to the set $\mathcal{A}_{proc}(v, v'')$.

Constraint (4) sets the capacity of the processes. Because of the structure of the graph, the capacity must be larger than the mass currently in the process as well as the mass on the way to the process. The set $\mathcal{A}_{cap}^-(v)$ represents the incoming arcs that arrive in vertex v such that they are in the process at time t. An example of this is shown in Fig. 4 where the blue arcs represents the capacity set $\mathcal{A}_{cap}^-(v)$ and the red arc the set $\mathcal{A}^-(v)$.

3.3. Input specific constraints

An input constraint must be added to assure, that the available input of each type is not exceeded:

$$\sum_{a\in\mathcal{A}^+(v)} x_a \le b_{i,t} \quad \forall v = (i,p,t,e) \in \mathcal{V}^F \cap (\mathcal{I}\times\mathcal{P}^F\times\mathcal{T}\times\mathcal{E}) \tag{5}$$

Where $b_{i,\,t}$ is the amount of biomass i available in time t.

At the biogas plant, there are regulations on percentage of e.g. energy crops in input mix, here denoted as the subset $\mathcal{I}^{EC}$ with the percentage given as η^{EC}. The constraints can be formulated as:

$$\sum_{\substack{v=(i,p,t,e)\in \\ \mathcal{V}^P\cap(\mathcal{I}^{EC}\times\mathcal{P}^P\times\mathcal{E})}} \sum_{a\in\mathcal{A}^-(v)} x_a \le \eta^{EC} \sum_{\substack{v=(i,p,t,e)\in\mathcal{V}^P \\ \cap(\mathcal{I}\times\mathcal{P}^P\times\mathcal{E})}} \sum_{a\in\mathcal{A}^-(v)} x_a \quad \forall t\in\mathcal{T} \tag{6}$$

OPEX and CAPEX for the biogas plant are implemented as stepwise linear functions. The resulting cost functions are concave and as they should be deducted from the income, it results in convex functions in the objective function that should be implemented using SOS2-variables. The related constraints are:

$$\sum_{v\in\mathcal{V}^P} \sum_{a\in\mathcal{A}^-(v)} x_a = \sum_{n\in\mathcal{N}} b_n^{plant} x_n^{SOS2} \tag{7}$$

$$\sum_{n\in\mathcal{N}} x_n^{SOS2} = 1 \tag{8}$$

$$\sum_{n\in\mathcal{N}} b_n^{plant} k_n^{SOS2} = \sum_{i\in\mathcal{I}} \sum_{p\in\mathcal{P}^P} \frac{T}{t_{i,p}^{min}} k_{i,p} \tag{9}$$

$$\sum_{n\in\mathcal{N}} k_n^{SOS2} = 1 \tag{10}$$

$$b_1^{plant} \le \sum_{i\in\mathcal{I}} \sum_{p\in\mathcal{P}^P} \frac{T}{t_{i,p}^{min}} k_{i,p} \le b_{end}^{plant} \tag{11}$$

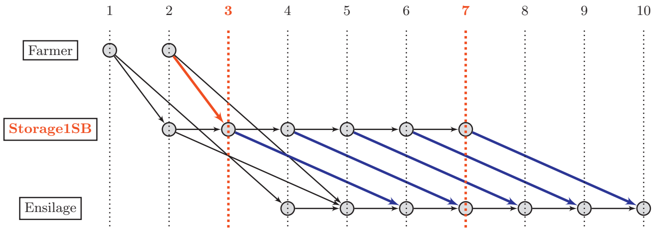

Fig. 3. Example of the process time constraints' related arcs, showing a process with a minimum process time of 1 week and a maximum process time of 5 weeks. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

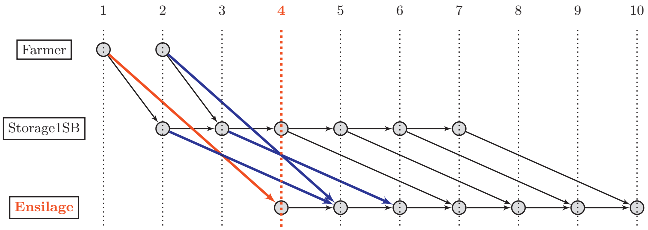

Fig. 4. Example of the capacity constraints' related arcs. The blue arcs describe the flow to the process that are included in the capacity in time 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The first two equations set the x_n^{SOS2}-variable by using the size of the biogas plant, b_n^{plant} in each breakpoint n. Eqs. (9)–(11) set the capacity of the plant and ensure that k_n^{SOS2} is an SOS2-variable, within the given boundaries of the cost function as given by the breakpoints b_1 and b_{end}.

3.4. Output specific constraints

The following constraint must be added to set the available input of biogas in each hour for each week based on the output from the biogas plant:

$$\sum_{\substack{v=(p,t)\in\\ \overline{\mathcal{V}}^P\cap\overline{\mathcal{P}}^P}} \sum_{a\in\overline{\mathcal{A}}^+(v)} \bar{x}_a = \sum_{\substack{v=(i,p,\lfloor\frac{t}{7\cdot 24}\rfloor+1,e)\\ \in\overline{\mathcal{V}}^P\cap(\mathcal{I}\times\overline{\mathcal{P}}^P\times\mathcal{E})}} \sum_{a\in\mathcal{A}^-(v)} \frac{x_a\overline{\eta}_i e}{7\cdot 24} \quad \forall t\in\overline{\mathcal{T}} \qquad (12)$$

Here the biogas yield of input type i is denoted as $\overline{\eta}_i$. This is used to calculate the biogas yield by multiplying with the energy content of the biomass type when it ends in the plant. The constant $7\cdot 24$ represents the number of hours per week and in the summation over v on the right hand side the relation between hours and weeks is ensured.

Further, the capacity constraint must be changed to address the problem of sizing power and heat plants where the deciding size is on the output from the process. For CHP plants, the constraint is further complicated by the fact that it is only the power production deciding the size of the plant. For power and heat processes, $\mathcal{P}^J$, the following constraint must be satisfied:

$$\sum_{a\in\overline{\mathcal{A}}^+_{decide}(v)} \bar{x}_a \le \bar{k}_p \quad \forall v=(p,t)\in\overline{\mathcal{V}}^J\cap(\overline{\mathcal{P}}^J\times\overline{\mathcal{T}}) \qquad (13)$$

Where the set $\overline{\mathcal{A}}^+_{decide}(v)$ are the arcs from vertex v determining the size of process p. For the rest of the processes on the output

For CHP plants and methanation, the flow is also constrained by a fixed range between the two products from the process, i.e. heat and power, and heat and natural gas. This fixed range is implemented by the following constraint:

$$\bar{x}_a = f_p\cdot \sum_{a'\in\overline{\mathcal{A}}^+_{extra}(v)} \bar{x}_{a'} \quad \forall v=(p,t)\in\overline{\mathcal{V}}^K\cap(\overline{\mathcal{P}}^K\times\mathcal{T}),\ a\in\overline{\mathcal{A}}^+_{main}(v) \qquad (14)$$

$\overline{\mathcal{A}}^+_{main}(v)$ is the set of arcs leaving process p in time t and arriving in a process that are of the main type, i.e. electricity for CHP and natural gas for methanation. $\overline{\mathcal{A}}^+_{extra}(v)$ is the set of arcs with origin in vertex v but not of the main type. f_p is the share of output going from process p on the main arcs of all the output from process p. The set $\overline{\mathcal{P}}^K$ describes the set of processes that have the fixed range specified.

Last, there is a fixed amount of heat that can be sold in hour t, $d_{p,t}$, only defined for heat processes $\overline{\mathcal{P}}^H$. This amount is the heat demand in the area and restricts the flow to the heat process. However, the heat can always be cooled away so the following constraint describes how much heat that cannot be sold in each hour:

$$\sum_{a\in\overline{\mathcal{A}}^-(v)} \bar{x}_a \le d_{p,t}+x^{left}_{p,t} \quad \forall v=(p,t)\in\overline{\mathcal{V}}^H\cap(\overline{\mathcal{P}}^H\times\overline{\mathcal{T}}) \qquad (15)$$

3.5. Transportation

Because the transportation planning problem is an additional complex problem to solve, the transportation side of the problem is simplified as in Boldrin et al. (2016). The procedure is to divide the area in which the plant lies into concentric circles with the plant in the center, see Fig. 5. This assumption can be used for ar-

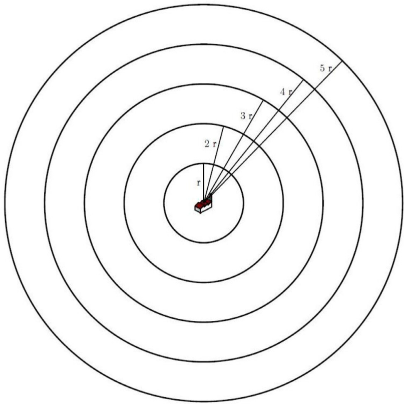

Fig. 5. The concentric circles around the plant is used to simplify the problem of transportation. The area between two circles is the annulus.

annulus—the region between two consecutive circles—the amount of biomasses is given and assumed equally spread out over the annulus. As shown in the objective function, there is a need to calculate the cost of collecting in each breakpoint, n'. This n' corresponds to one of the radii shown in the figure.

To calculate the costs, the amount of biomass in the annulus between n' and $n'-1$, $am_{i,n'}$, must be obtained. From this the average transportation distance, $\Delta d_{i,n'}$, for the accumulated mass, $AM_{i,n'}$, for the biomass type i in breakpoint n' can be calculated by:

$$\Delta d_{i,n'} = \sum_{j=1}^{n'} \frac{am_{ij}}{AM_{i,n'}} \cdot \Delta r_j \tag{16}$$

Here am_{ij} denotes the mass that can be collected within the radius r_j and r_{j-1}, and Δr_j denotes the average distance from the given area to the plant. Δr_j can be calculated by finding the average area, ΔA_j, of the circles using the area of circle j and $j-1$, denoted by A_j and A_{j-1}:

$$\Delta A_j = \frac{A_j + A_{j-1}}{2} \tag{17}$$

Which can be reduced to:

$$\pi\ \Delta r_j^2 = \frac{\pi\ r_j^2 + \pi\ r_{j-1}^2}{2} \tag{18}$$

And finally:

$$\Delta r_j = \sqrt{\frac{r_j^2 + r_{j-1}^2}{2}} \tag{19}$$

To use the Euclidean distance, 2-norm distance, from the midpoint to the average radius' endpoint in 2D, seems to be a fair assumption as the road network in Denmark, where the case study is performed, is rather fine-meshed. In other countries it might be relevant to use distance measures like the Manhattan distance, or other distance measures.

The trucks used for transportation depends on the type of input. Therefore, the capacity, velocity and costs of each truck depend on the input type. The cost, $c_{i,n'}^{TRANS}$ of each biomass type transported to the plant in each breakpoint n' can be expressed by the following formula:

$$c_{i,n'}^{TRANS} = 2 \cdot \frac{am_{i,n'}\ \Delta d_{i,n'}\ c_i^{truck}}{k_i^{truck}\ v_i} + \frac{am_{i,n'}\ (t_i^{load}\ c_i^{load} + t_i^{unload}\ c_i^{unload})}{k_i^{truck}} \tag{20}$$

The first part of the right hand side is the transportation time to and from the farmer, hence the multiplication with 2. Here c_i^{truck} is the hourly cost of transporting input type i on the truck used for transportation, k_i^{truck} is the capacity of the truck, and v_i is the velocity of the truck. The second part is the amount of time it takes to load/unload the truck, t_i^{load} and t_i^{unload}, times the cost of loading/unloading, c_i^{load} and c_i^{unload} depending on the type of machines that is to be used divided by the capacity of each load. This is an approximation to the real-life problem as we assume that the trucks only do full-load trips even though this most likely is not the case.

The cost can be used for the digestate as well, but considering that as much digestate as possible is delivered back to the livestock keepers, it is only a small amount that has to be sent elsewhere. The exact amount depends on the willingness of farmers to receive more than they delivered to the plant. The amount that can be sent to these places is also to be obtained and structured as above. However, the cost is different as the amount sent to the animal farmers is already taken care of in the first part of Eq. (20). The only thing that is missing is the loading/unloading of all digestate as well as the transportation to the new places. Transportation to the new places are found by:

$$c_{n'}^{TRANS,xdig} = 2 \cdot \frac{am_{n'}^{dig}\ \Delta d_{n'}^{dig}\ c^{truck,dig}}{k^{truck,dig}\ v^{dig}} \tag{21}$$

Where the same notation as above is used but instead of an index i the superscript dig is used to denote the digestate.

The handling costs are not depending on the amount available in each circle but can be expressed by:

$$c^{HANDLING,dig} = (t^{load,dig}\ c^{load,dig} + t^{unload,dig}\ c^{unload,dig}) \tag{22}$$

If the cost functions, $c_{i,n'}^{TRANS}$ and $c_{n'}^{TRANS,xdig}$, are plotted, they are stepwise linear and convex function. As we are maximizing the negative functions, the terms are concave in the objective function and hence they can be modeled using linear variables. Therefore, the cost functions given above are recalculated to be the slope of the cost function in the interval m by:

$$c_{i,m}^{TRANS} = \frac{c_{in^+(m)}^{TRANS} - c_{in^-(m)}^{TRANS}}{am_{in^+(m)}} \tag{23}$$

Where $n^-(m)/n^+(m)$ denotes the breakpoints before and after m. This formula can also be used on $c_{n'}^{TRANS,xdig}$ to get the cost for $c_m^{TRANS,xdig}$.

The constraints that must be added to the model related to transportation are:

$$\sum_{m \in \mathcal{M}} x_{i,m}^{trans} = \sum_{\substack{v=(i,p,t,e)\in \\ \mathcal{V}^T \cap (\mathcal{P}^T \times \mathcal{T} \times \mathcal{E})}} \sum_{a \in \mathcal{A}^+(v)} x_a \quad \forall i \in \mathcal{I} \tag{24}$$

$$x_{i,m}^{trans} \le am_{i,m} \quad \forall i \in \mathcal{I},\ m \in \mathcal{M} \tag{25}$$

Where $\mathcal{V}^T$ are the vertices from which transportation are made as specified by the user.

For the digestate, the amount that cannot be sent back to the animal farmers is calculated in the model by:

$$x^{\neg manure} \ge \sum_{\substack{v=(i,p,t,e)\in \\ \mathcal{V}^P \cap (\mathcal{P}^P \times \mathcal{T} \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} x_a \eta^{plant} - \sum_{v \in \mathcal{V}^M} \sum_{a \in \mathcal{A}^+(v)} x_a \gamma \tag{26}$$

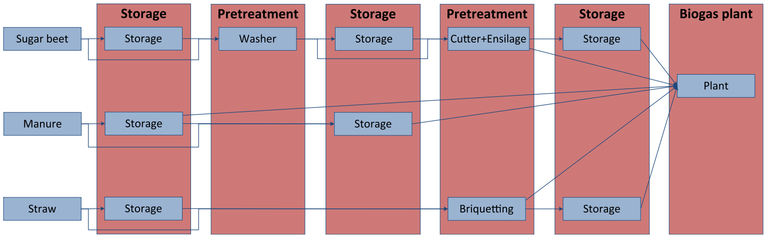

Fig. 6. The network on the input side.

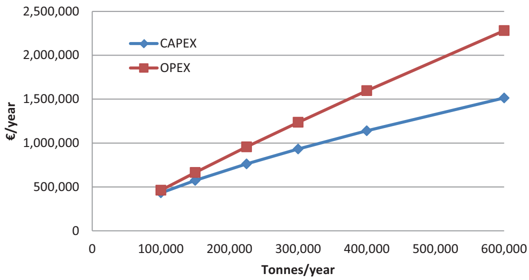

Fig. 7. The step-wise linear functions of CAPEX and OPEX.

Where $x^{\neg manure}$ is the amount that cannot be sent back to the manure suppliers and γ represents the percentage of delivered manure that can be sent back. To find the amount that can be sent back on each segment, the following equations are used:

$$x_m^{trans,xdig} \leq am_m^{dig} \quad \forall m \in \mathcal{M} \tag{27}$$

$$\sum_{m \in \mathcal{M}} x_m^{trans,xdig} \leq x^{\neg manure} \tag{28}$$

4. Case study

A small case study was conducted in order to evaluate straw, sugar beet, and pig manure as feedstock to the biogas plant. The case study is chosen to be as close to real-life as possible but is not intended to be replicating a planned plant as the extensive data needed cannot be gathered from a specific plant. North-West of Denmark is used as the placement. The data used is based on results on energy yields, mass losses, and cost estimates of pretreatment and transportation etc. from the BioChain project (Abildgaard, 2016), and economic data on current and future Danish biogas plants which have been used to make the cost curves for CAPEX and OPEX for the biogas plants.[1]

The case study includes two pretreatment facilities for sugar beet, one pretreatment for straw, and no pretreatment for manure. It is assumed that the pretreatments are located at the biogas plant. The network on the input side is shown in Fig. 6 and the economic data for each process can be seen in Tables C.1 and C.2 in Appendix C. The transportation data can be seen in Table C.3 also in Appendix C.

The step-wise linear function of OPEX and CAPEX on the plant can be seen in Fig. 7. From this figure it is seen, that the minimum size of the plant is set to 100,000 tonnes of input per year and the maximum size is set to 600,000 tonnes per year. The maximum size is set because of a lack of data for larger biogas plants.

The CAPEX, OPEX and efficiency data for the output processes, gathered from various sources, are listed in Table C.4 in Appendix C. We have assumed that the cost of cooling the excess heat is included in the costs of CHP's, boiler, and methanation. The network used can be seen in Fig. 8. In the network a transformation from cubic meter biogas to cubic meter natural gas or megawatt hour is made such that the output in the demand is given in cubic meter natural gas for the NG distribution grid and in megawatt hour for heat and electricity. In order to make this transformation from the upgrading process methanation, an extra process with no losses and no process time is inserted between methanation and heat storage to allow for two different units on the output. This process is called Nm3ToMWh. For the specific methanation type, there is no need for pressure regulation as the resulting biomethane will have a pressure of 40 bars, which is the pressure needed for injection into the distribution grid.

In Denmark, biogas is state subsidized based on the end use of the biogas. Table 1 gives an overview of this support. The support scheme implies that the electricity price is fixed throughout the year. However, for methanation which uses a lot of electricity to produce the natural gas, the electricity price is based on the price from 2015 in Western Denmark and is an hourly price. Furthermore, the upgraded biogas will earn both the support and the natural gas price. The exact support for the upgraded biogas through

[1] The data is based on economic data from Danish biogas plants to apply for financial aid from the Danish Energy Agency. An anonymized version of the costs

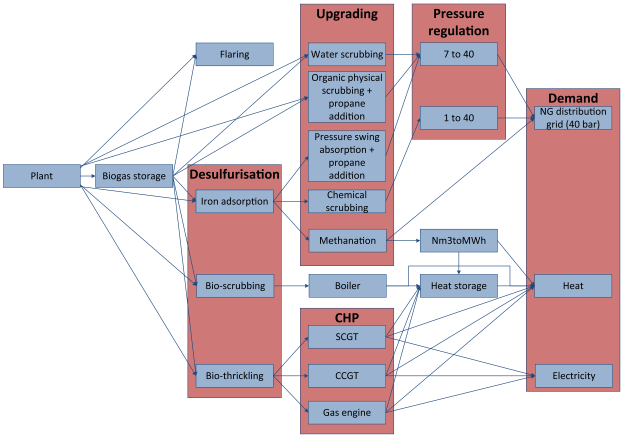

Fig. 8. The network on the output side.

Table 1
The Danish support scheme for biogas production.

End use	Support
Electricity	Fixed price of electricity: 163 euros per megawatt hour
Heat	No support
Natural gas	0.64 euros per normal cubic meter NG

Denmark using methanation. The argument for having subsidy on the upgraded gas is that it is a waste treatment of manure, however, when the methanation production is used, the outcome is more gas per input of biogas and thus an unfair amount of subsidy for methanation. An argument for keeping the subsidy for methanation at the same level as for the other upgrading technologies could be that there is an increased focus in Denmark on converting electricity to other fuels. Therefore, we assume that the methanation process will earn the same amount of subsidy. Due to lack of data, the natural gas price variations are based on the natural gas price for Denmark in 2013. To convert it into the price level of 2015, the prices from 2013 have been increased to achieve the average price of 2015. The natural gas price is a daily price. As given by the Danish regulation, the maximum amount of energy crops that can be used in the plant is 12% in order to achieve subsidies.

The methane percentage of the biogas is assumed to be 65% and the amount of flaring needed because of plant failures etc. is assumed to be 5%. The assumed value of digestate is 8.84 euros per ton (Birkmose, Hjort-Gregersen, & Stefanek, 2013), and the assumed mass passing through the biogas plant is 91.93% (Boldrin et al., 2016). This percentage is assumed constant as the most significant part of the input is water from the manure, even though the amount is dependent on the input mix and pretreatments used.

5. Results and discussion

The model has been implemented in GAMS-software, version 24.4 and was solved using CPLEX-solver, version 12.6, on a Dell Latitude E6430 with 2.4 gigahertz CPU, 8 gigabytes RAM, and a Windows 7 Enterprise 64-bit operating system. The model has been

Table 2
Results of the model run.

Objective	26,671,879	Euros per year
Income, excluding support	18,158,065	Euros per year
Support	33,577,639	Euros per year
Cost	25,063,825	Euros per year
Size of biogas plant	600,000	Tonnes per year
Sugar beet	0	Tonnes per year
Manure	528,000	Tonnes per year
Straw	72,000	Tonnes per year
Biomethane	52,465,062	Cubic meter
Electricity	0	Megawatt hour
Heat	36,017	Megawatt hour

solved using the Barrier algorithm in CPLEX as it showed to reduce the running time to less than half than by applying the default setting.

Because of the maximum size of the plant of 600,000 tonnes of input per year, the relaxed mixed integer programming (RMIP) problem finds integer solutions for many of the scenarios, i.e. solutions where the SOS2 variables are adjacent and at most two of the variables are non-zero. Therefore, all results have been found using the RMIP model and if the solution was not integer, the MIP was run. The RMIP runs can be performed within five minutes and a MIP run is in the worst-case done within 21 minutes.

The results of the data described in Section 4 can be seen in Table 2. The table shows that the plant is only profitable because of the support, underlining the necessity of optimizing the supply chain. It is seen that the optimal way of producing is by building as large as possible and using manure and straw as input biomasses. The location of the plant determines the size of the plant so if the input biomasses were farther from the plant, the size would—at some point—decrease. The straw is pretreated before it is stored and used continuously over the year while the manure is used continuously over the year implying no investment in storage for the manure.

The straw is used continuously over the year at the limit of 12% at the plant, with a large storage after the pretreatment. This means that the cost of storage for straw is small when including

Table 3
Capacities on the output processes for the model run.

Gas storage	11,620	Cubic meter BG
Iron adsorption	3,981	Cubic meter BG
Methanation	3,981	Cubic meter BG
Heat storage	14.3	Megawatt

the extra biogas yield it gives. The usage of straw throughout the year gives a constant output that must be handled by the output processes. The size of the processes on the output side can be seen in Table 3 and here it shows that upgrading to biomethane using methanation is optimal, even though the heat demand is fully covered in some periods.

The heat storage is used to a small extent, corresponding to approximately 16 times the smallest heat demand or 2 times the largest heat demand, but this is not enough to cover the amount of heat produced, so a significant amount of heat is cooled off. The extra cost of the heat storage does not outweigh the extra support obtained due to the extra production of biomethane from methanation.

The sizes of the gas and heat storage indicate that the biogas can be utilized better by including the output side as the flexibility of the storage can be used. The graphs in Fig. 9 show the usage of the gas and heat storage in the first week of the modeling year together with the normalized electricity price. The natural gas price is not shown as it did not affect the usage of the biogas. For both graphs it can be seen that there is a reaction to an increase in electricity prices. For the gas storage the reaction is seen before the actual peak as there is a delay from the gas storage to the methanation. On the highest peak in day 5 it can be seen that the gas is stored in the gas storage while the heat, which was previously stored in the heat storage, is discharged to fulfill the heat demand. The gas storage is discharged most of the time to supply the methanation with more biogas whereas the heat storage is discharged more intensely in some periods, e.g. when there is no methanation taking place as in day 5. The many charges and discharges in the heat storage happens as there are no cost for charging or discharging, the OPEX for the storage is zero, and a lot of the heat generated has no value as it must be cooled off. The amount of heat cooled in each time step is the amount between the red and light blue line.

5.1. Sensitivity analysis

Because the total costs of each of the output processes are at a similar level, different scenarios related to the output data have been chosen to investigate the impact of changes. However, these scenarios have to affect the methanation process a lot as the difference between the methanation process and the second best solution is high. The chosen scenarios are shown in Table 4. The result of scenarios 1–4 can be seen in Fig. 10. As the first result

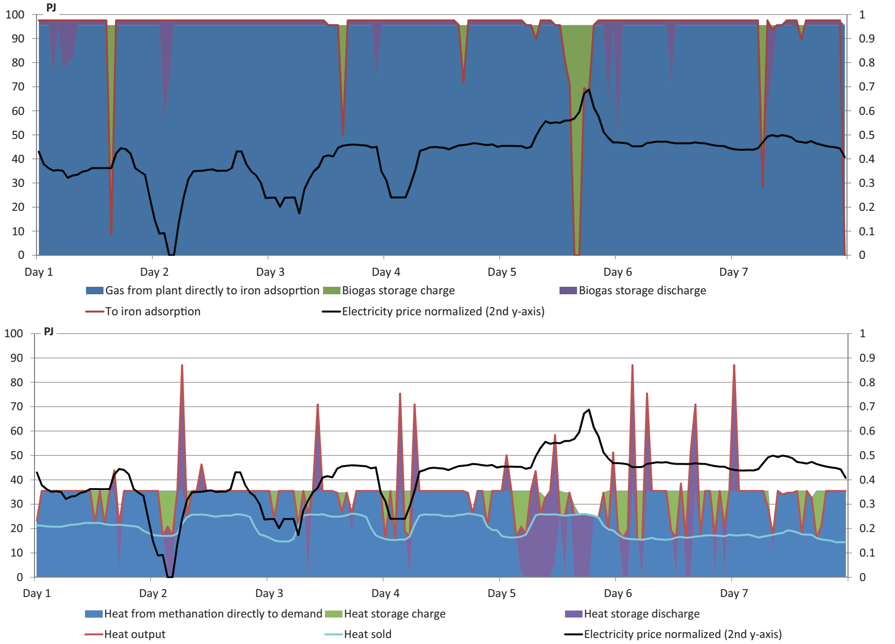

Fig. 9. Usage of the gas and heat storage for the first week of the year. The top graph shows the gas storage usage and the graph below shows the heat storage usage. (For

Table 4
Scenarios used for the sensitivity analysis.

Scenario	Natural gas price	Electricity price	Heat demand	Subsidy, biomethane
1	50%	–	–	–
2	–	150%	-	–
3	–	–	50%	–
4	50%	150%	50%	–
5	–	–	–	50%
6	50%	–	–	50%
7	–	150%	–	50%
8	–	–	50%	50%

shows that the model chooses to upgrade the biogas, the natural gas price might influence the solution such that another setting will be chosen if the natural gas price is decreased. To determine the effect, the natural gas price is decreased to 50%. The methanation process is still the optimal way of producing even though the profit decreases. The decrease in the objective function value is approximately 20% and is due to the loss in the sales price of the biomethane.

For the electricity price, the methanation process might become too expensive if the electricity price increase. Here, the electricity price is increased to 150% to see if it affects the solution. The scenario shows that the solution is stable to changes in electricity prices as there is only a reduction of around 7% from the reference scenario. This can be explained by the low effect as it affects only the OPEX of methanation.

The heat demand in the region could be of interest. If the heat demand is decreased, methanation will not be used as much because the heat cannot be sold. The demand is decreased to 50% and from Fig. 10 it is seen that the objective function is close to the reference scenario. The change in heat demand only changes the amount that can be sold and as this amount adds a small income to the objective function, the objective function value is changed with only 2%.

The combination with a decrease in natural gas price, an increase in electricity price, and a decrease in heat demand is used. The objective function value is affected by all changes and is now 29% less than in the reference scenario. This is still not enough to change the optimal investments and therefore the extra scenarios with a reduction in subsidy for biomethane are introduced.

Last, the subsidy for biomethane is set to 50% of the current support and is also combined with the regulation of natural gas price, electricity price and heat demand. The results can be seen in Fig. 11. Here, it is seen that the only scenarios where the methanation process is not used is when the subsidy decrease is combined with natural gas price reductions or an increase in electricity price, meaning that the production cost of methanation is getting more expensive. Further, the reduction of support as well as the combination with a decrease in heat demand gives a solution with an objective function value close to scenarios 6 and 7 but with methanation as the best investment. This shows that given a decrease in support, the possible investments on the output side are more responsive to fluctuations in prices than when the support is not decreased.

6. Conclusion

Biogas and bioenergy projects in general have received growing attention the last years in order to make them profitable by optimizing the supply chain. However, the literature is mostly focused on the supply of biomasses to the plant and does not consider the possible gains of including storage possibilities on the output side.

In this article, a mathematical model optimizing production and investment for a biogas plant has been presented spanning the full supply chain from farmer to energy demand. The model has been applied to a specific location in Denmark. The case study shows that for the specific location, given the assumptions on efficiencies and costs, the plant should be built as large as possible within the given sizes and use methanation to upgrade the biogas to biomethane to increase income from biogas sales and to cover the heat demand in the region.

The inclusion of the output side is utilized by using a gas storage and a heat storage and therefore the biogas can be used when

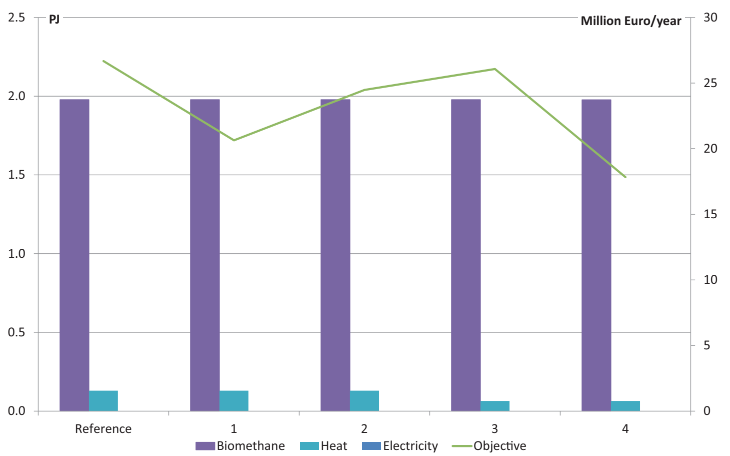

Fig. 10. Results of scenarios 1–4 showing the biomethane, heat, and electricity production on the left axis and the objective function value on the right axis.

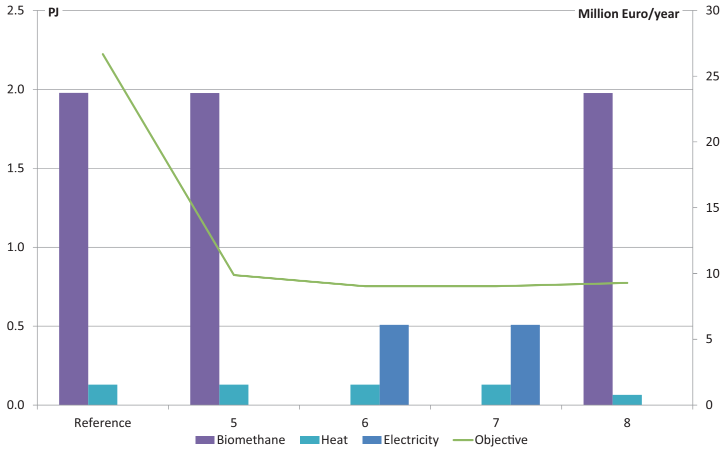

Fig. 11. Results of scenarios 5–8 showing the biomethane, heat, and electricity production on the left axis and the objective function value on the right axis.

the demand of heat is present or stored considering the cost of storage.

The paper demonstrates that by careful planning of the complete supply chain, profitable biogas plants can be constructed. Even though the model gives an overall profitable solution, it does not ensure all stakeholders will get their share of the profit which might spoil the motivation for participating in the project. Therefore, it is interesting to study how the model can ensure a fair distribution of profit among the stakeholders.

Acknowledgment

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Appendix A. Nomenclature

Parameters

AM_{i}, n'	Accumulated amount of biomass for biomass type i in breakpoint n'
A_j	Area of circle j
T	Number of weeks in a year
ΔA_j	Average area of circle j and circle $j-1$
$\Delta d_{i,n'}\,(\Delta d_{n'}^{dig})$	Average transportation distance for biomass i (digestate) in breakpoint n
Δr_j	Average distance from center to the biomasses in circle j
η^{EC}	Percentage energy crops allowed in input mix
$\eta^{available}$	Amount not flared
η^{plant}	Mass after biogas plant %
$\eta_{i,p',p}/\overline{\eta}_{p',p}$	Mass left after process p coming from process p'
γ	Percentage of mass of supplied manure that can be returned as digestate
$\overline{\rho}_{p,t}$	Price of end product p in time t
ρ^{dig}	Price of digestate
$\rho_p^{support}$	Support process p
$am_{i,m}\,(am_m^{dig})$	Amount of biomass (digestate) transported on segment m
$am_{i,n'}\,(am_{n'}^{dig})$	Amount of biomass (digestate) in the annulus between n' and $n'-1$
b_n^{plant}	Max. capacity of plant in breakpoint n
$b_{i,\,t}$	Biomass i available at time t
$c^{HANDLING,\ dig}$	Handling cost of digestate
$c_n^{OPEX,SOS2}/c_n^{CAPEX,SOS2}$	OPEX/ CAPEX in breakpoint n for the plant
$c_{i,p,t}^{OPEX,var}$	Variable OPEX for input type i, process p and time t p and time t
$c_{i,p}^{OPEX}/c_{i,p}^{CAPEX}$ $(\overline{c}_p^{OPEX}/\overline{c}_p^{CAPEX})$	OPEX/CAPEX for biomass (gas) process p for input type i
$c_{i,m}^{TRANS}\,(c_m^{TRANS,xdig})$	Transport cost for biomass type i (digestate not sent to the manure supplier) on each segment m
c_i^{prod}	Production cost of biomass type i
c_i^{load}/c_i^{unload} $(c^{load,\ dig}/c^{unload,\ dig})$	Cost of loading/unloading biomass i (digestate)
$c_i^{truck}\,(c^{truck,dig})$	Cost of using truck for biomass i (digestate)
$c_{i,n'}^{TRANS}$	Cost of each biomass type transported to the plant in each breakpoint n'
$c_{n'}^{TRANS,xdig}$	Transportation cost for digestate not delivered to the manure suppliers in breakpoint n
$d_{p,t}$	Demand of end product in hour t—only defined for heat
f_p	Fixed amount going to process p from a $\mathcal{P}^K$ *process*
$k_i^{truck}\,(k^{truck,dig})$	Capacity of the truck used for transportation of biomass i (digestate)
$t_{i,p}^{min}$	Minimum process time of process p for in-

t_i^{load}/t_i^{unload} ($t^{load,dig}/t^{unload,dig}$)	Time used for loading/unloading biomass i (digestate)
$v_i(v^{dig})$	Velocity of truck used for transportation of biomass i (digestate)
Sets	
$\mathcal{A}(v',v)(\overline{\mathcal{A}}(v',v))$	Arcs from vertex v' to vertex v
$\mathcal{A}^-(v)/\mathcal{A}^+(v)$ ($\overline{\mathcal{A}}^-(v)/\overline{\mathcal{A}}^+(v)$)	Input (output) side arcs entering/leaving vertex v
$\mathcal{A}_{proc}(v,v'')$ ($\overline{\mathcal{A}}_{proc}(v,v'')$)	Process time arcs from vertex v to vertex v''
$\mathcal{E}$	The set of possible energy content
$\mathcal{I}^{EC}$	Subset of biomasses that are energy crops
$\mathcal{I}$	Biomass types
$\mathcal{M}$	Line segments
$\mathcal{N}$	breakpoints
$\mathcal{P}(\overline{\mathcal{P}})$	Input (output) processes
$\mathcal{P}^F$	Farmer processes
$\mathcal{P}^I(\overline{\mathcal{P}}^I)$	Inner processes
$\mathcal{P}^P(\overline{\mathcal{P}}^P)$	The plant process on the input (output) side
$\mathcal{P}^T$	Transportation processes
$\mathcal{T}/\overline{\mathcal{T}}$	Input (output) time steps
$\mathcal{V}(\overline{\mathcal{V}})$	Input (output) vertices
$\mathcal{V}^F$	Vertices of farmer processes
$\mathcal{V}^I(\overline{\mathcal{V}}^I)$	Vertices of the inner processes
$\mathcal{V}^M$	Vertices of the manure farmer's process
$\mathcal{V}^P(\overline{\mathcal{V}}^P)$	Plant vertices on the input (output) side
$\mathcal{V}^T$	Vertices of the transportation processes
$\overline{\mathcal{A}}^+_{decide}(v)$	The set of arcs leaving vertex v which defines the capacity of the process it leaves
$\overline{\mathcal{A}}^+_{extra}(v)$	The set of arcs with origin in vertex v but not of the main type
$\overline{\mathcal{A}}^+_{main}(v)$	The set of arcs leaving vertex v and arriving in a process that are of the main type
$\overline{\mathcal{P}}^J$	Processes on the output side with capacity specified on output
$\overline{\mathcal{P}}^K$	Processes where the inflow is fixed
$\overline{\mathcal{V}}^E$	Vertices of the end processes
$\overline{\mathcal{V}}^H$	End vertex for heat
$\overline{\mathcal{V}}^J$	Vertices on the output side with capacity specified on output
$\overline{\mathcal{V}}^K$	Vertices where the inflow is fixed
Variables	
k_n^{SOS2}	If the size of the plant is near breakpoint n
$k_{i,p}/\overline{k}_p$	Capacity of biomass/gas process p for biomass type i
$x_{p,t}^{left}$	Not sold due to lack of demand
x^{manure}	Digestate not sent to manure suppliers
$x_m^{trans,xdig}$	Extra digestate transported on segment m
x_n^{SOS2}	Biomasses to the plant in breakpoint n
$x_a/\overline{x}_a$	Flow on biomass/gas arc a
$x_{i,m}^{trans}$	Biomass i transported on segment m

Appendix B. Model

$$
\begin{aligned}
\max & \sum_{v\in\mathcal{V}^P}\sum_{a\in\mathcal{A}^-(v)} x_a\,\eta^{plant}\,\rho^{dig} \\
&+ \sum_{\substack{v=(p,t)\in\\ \overline{\mathcal{V}}^E\cap(\overline{\mathcal{P}}^E\times\overline{\mathcal{T}})}}\sum_{a\in\overline{\mathcal{A}}^-(v)} (\overline{x}_a\,\rho_p^{support} + \overline{x}_a\,\overline{\rho}_{p,t}\,\eta^{available}) \\
&- \sum_{p\in\overline{\mathcal{P}}}\sum_{t\in\overline{\mathcal{T}}} x_{p,t}^{left}\,\overline{\rho}_{p,t}\,\eta^{available} - \sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}^F\cap(\mathcal{I}\times\mathcal{P}^F\times\mathcal{T}\times\mathcal{E})}}\sum_{a\in\mathcal{A}^+(v)} x_a\,c_i^{prod} \\
&- \sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}\cap(\mathcal{I}\times\mathcal{P}\times\mathcal{T}\times\mathcal{E})}}\sum_{a\in\mathcal{A}^-(v)} x_a\,(c_{i,p}^{OPEX} + c_{i,p,t}^{OPEX,var}) \\
&- \sum_{\substack{v=(p,t)\in\\ \overline{\mathcal{V}}\cap(\overline{\mathcal{P}}\times\overline{\mathcal{T}})}}\sum_{a\in\overline{\mathcal{A}}^-(v)} \overline{x}_a\,\overline{c}_p^{OPEX} \\
&- \sum_{i\in\mathcal{I}}\sum_{p\in\mathcal{P}} k_{i,p}\,\frac{T}{t_{i,p}^{min}}\,c_{i,p}^{CAPEX} - \sum_{p\in\overline{\mathcal{P}}} \overline{k}_p\,\overline{c}_p^{CAPEX} - \sum_{n\in\mathcal{N}} x_n^{SOS2}\,c_n^{OPEX,SOS2} \\
&- \sum_{n\in\mathcal{N}} k_n^{SOS2}\,c_n^{CAPEX,SOS2} - \sum_{i\in\mathcal{I}}\sum_{m\in\mathcal{M}} x_{i,m}^{trans}\,c_{i,m}^{TRANS} \\
&- \sum_{m\in\mathcal{M}} x_m^{trans,xdig}\,c_m^{TRANS,xdig} \\
&- \sum_{v\in\mathcal{V}^P}\sum_{a\in\mathcal{A}^-(v)} x_a\,\eta^{plant}\,c^{HANDLING,dig}
\end{aligned}
$$

Subject to:

$$
\sum_{\substack{v'=(i',p',t',e')\in\\ \mathcal{V}\cap(\mathcal{I}\times\mathcal{P}\times\mathcal{T}\times\mathcal{E})}}\sum_{a\in\mathcal{A}(v',v)} x_a\,\eta_{i,p',p} = \sum_{a\in\mathcal{A}^+(v)} x_a
$$

$$
\forall v=(i,p,t,e)\in\mathcal{V}^I\cap(\mathcal{I}\times\mathcal{P}^I\times\mathcal{T}\times\mathcal{E})
$$

$$
\sum_{\substack{v'=(i,p',t',e')\in\\ \mathcal{V}\cap(\mathcal{P}\times\mathcal{T}\times\mathcal{E})\mid p\neq p'}}\sum_{a\in\mathcal{A}(v',v)} x_a\,\eta_{i,p',p}
\le \sum_{\substack{v''=(i,p'',t'',e'')\in\\ \mathcal{V}\cap(\mathcal{P}\times\mathcal{T}\times\mathcal{E})\mid p\neq p''}}\sum_{a\in\mathcal{A}_{proc}(v,v'')} \frac{x_a}{(\eta_{i,p,p})^{t''-t}}
$$

$$
\forall v=(i,p,t,e)\in\mathcal{V}^I\cap(\mathcal{I}\times\mathcal{P}^I\times\mathcal{T}\times\mathcal{E})
$$

$$
\sum_{v=(i,p,t,e)\in\mathcal{V}\cap\mathcal{E}}\sum_{a\in\mathcal{A}^-(v)} x_a + \sum_{v=(i,p,t,e)\in\mathcal{V}\cap\mathcal{E}}\sum_{a\in\mathcal{A}^-_{cap}(v)} x_a \le k_{i,p}
$$

$$
\forall (i,p,t)\in\mathcal{I}\times\mathcal{P}\times\mathcal{T}
$$

$$
\sum_{a\in\mathcal{A}^+(v)} x_a \le b_{i,t} \quad \forall v=(i,p,t,e)\in\mathcal{V}^F\cap(\mathcal{I}\times\mathcal{P}^F\times\mathcal{T}\times\mathcal{E})
$$

$$
\sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}^P\cap(\mathcal{I}^{EC}\times\mathcal{P}^P\times\mathcal{E})}}\sum_{a\in\mathcal{A}^-(v)} x_a \le \eta^{EC} \sum_{\substack{v=(i,p,t,e)\in\mathcal{V}^P\\ \cap(\mathcal{I}\times\mathcal{P}^P\times\mathcal{E})}}\sum_{a\in\mathcal{A}^-(v)} x_a \quad \forall t\in\mathcal{T}
$$

$$
\sum_{v\in\mathcal{V}^P}\sum_{a\in\mathcal{A}^-(v)} x_a = \sum_{n\in\mathcal{N}} b_n^{plant}\,x_n^{SOS2}
$$

$$
\sum_{n\in\mathcal{N}} x_n^{SOS2} = 1
$$

$$
\sum_{n\in\mathcal{N}} b_n^{plant}\,k_n^{SOS2} = \sum_{i\in\mathcal{I}}\sum_{p\in\mathcal{P}^P} \frac{T}{t_{i,p}^{min}}\,k_{i,p}
$$

$$
\sum_{n\in\mathcal{N}} k_n^{SOS2} = 1
$$

$$
b_1^{plant} \le \sum_{i\in\mathcal{I}}\sum_{p\in\mathcal{P}^P} \frac{T}{t_{i,p}^{min}}\,k_{i,p} \le b_{end}^{plant}
$$

$$\sum_{\substack{v'=(p',t')\in\\ \overline{\mathcal{V}}\cap(\overline{\mathcal{P}}\times\overline{\mathcal{T}})}} \sum_{a\in\overline{\mathcal{A}}(v',v)} \bar{x}_a\,\bar{\eta}_{p',p} = \sum_{a\in\overline{\mathcal{A}}^{+}(v)} \bar{x}_a \quad \forall v=(p,t)\in\overline{\mathcal{V}}^{I}\cap(\overline{\mathcal{P}}^{I}\times\overline{\mathcal{T}})$$

$$\sum_{\substack{v'=(p',t')\in\\ \overline{\mathcal{V}}\cap(\overline{\mathcal{P}}\times\overline{\mathcal{T}})|p\neq p'}} \sum_{a\in\overline{\mathcal{A}}(v',v)} \bar{x}_a\,\bar{\eta}_{p',p} \leq \sum_{\substack{v''=(p'',t'')\in\\ \overline{\mathcal{V}}\cap(\overline{\mathcal{P}}\times\overline{\mathcal{T}})|p\neq p''}} \sum_{a\in\overline{\mathcal{A}}_{proc}(v,v'')} \frac{\bar{x}_a}{(\bar{\eta}_{pp})^{t''-t}}$$

$$\forall v=(p,t)\in\overline{\mathcal{V}}^{I}\cap(\overline{\mathcal{P}}^{I}\times\overline{\mathcal{T}})$$

$$\sum_{v=(p,t)\in\overline{\mathcal{V}}} \sum_{a\in\overline{\mathcal{A}}^{-}(v)} \bar{x}_a + \sum_{v=(p,t)\in\overline{\mathcal{V}}} \sum_{a\in\overline{\mathcal{A}}^{-}_{cap}(v)} \bar{x}_a \leq \bar{k}_p \quad \forall (p,t)\in\overline{\mathcal{P}}\times\overline{\mathcal{T}}$$

$$\sum_{\substack{v=(p,t)\in\\ \overline{\mathcal{V}}^{P}\cap\overline{\mathcal{P}}^{P}}} \sum_{a\in\overline{\mathcal{A}}^{+}(v)} \bar{x}_a = \sum_{\substack{v=(i,p,\lfloor\frac{t}{7\cdot 24}\rfloor+1,e)\\ \in\overline{\mathcal{V}}^{P}\cap(\mathcal{I}\times\overline{\mathcal{P}}^{P}\times\mathcal{E})}} \sum_{a\in\mathcal{A}^{-}(v)} \frac{x_a\,\bar{\eta}_i\, e}{7\cdot 24} \quad \forall t\in\overline{\mathcal{T}}$$

$$\sum_{a\in\overline{\mathcal{A}}^{+}_{decide}(v)} \bar{x}_a \leq \bar{k}_p \quad \forall v=(p,t)\in\overline{\mathcal{V}}^{J}\cap(\overline{\mathcal{P}}^{J}\times\overline{\mathcal{T}})$$

$$\bar{x}_a = f_p \sum_{a'\in\overline{\mathcal{A}}^{+}_{extra}(v)} \bar{x}_{a'} \quad \forall v=(p,t)\in\overline{\mathcal{V}}^{K}\cap(\overline{\mathcal{P}}^{K}\times\mathcal{T}),\ a\in\overline{\mathcal{A}}^{+}_{main}(v)$$

$$\sum_{a\in\overline{\mathcal{A}}(v)} \bar{x}_a \leq d_{p,t} + x^{left}_{p,t} \quad \forall v=(p,t)\in\overline{\mathcal{V}}^{H}\cap(\overline{\mathcal{P}}^{H}\times\overline{\mathcal{T}})$$

$$\sum_{m\in\mathcal{M}} x^{trans}_{i,m} = \sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}^{T}\cap(\mathcal{P}^{T}\times\mathcal{T}\times\mathcal{E})}} \sum_{a\in\mathcal{A}^{+}(v)} x_a \quad \forall i\in\mathcal{I}$$

$$x^{trans}_{i,m} \leq am_{i,m} \quad \forall i\in\mathcal{I},\ m\in\mathcal{M}$$

$$x^{\neg manure} \geq \sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}^{P}\cap(\mathcal{P}^{P}\times\mathcal{T}\times\mathcal{E})}} \sum_{a\in\mathcal{A}^{-}(v)} x_a\eta^{plant} - \sum_{v\in\mathcal{V}^{M}} \sum_{a\in\mathcal{A}^{+}(v)} x_a\gamma$$

$$x^{trans,xdig}_{m} \leq am^{dig}_{m} \quad \forall m\in\mathcal{M}$$

$$\sum_{m\in\mathcal{M}} x^{trans,xdig}_{m} \leq x^{\neg manure}$$

$$x_a \geq 0 \quad \forall a\in\mathcal{A}$$

$$\bar{x}_a \geq 0 \quad \forall a\in\overline{\mathcal{A}}$$

$$x^{left}_{p,t} \geq 0 \quad \forall p\in\overline{\mathcal{P}},\ t\in\overline{\mathcal{T}}$$

$$k_{i,p} \geq 0 \quad i\in\mathcal{I},\ p\in\mathcal{P}$$

$$\bar{k}_p \geq 0 \quad \forall p\in\overline{\mathcal{P}}$$

$$x^{SOS2}_{n}, k^{SOS2}_{n} \in SOS2 \quad \forall n\in\mathcal{N}$$

$$x^{trans}_{i,m} \geq 0 \quad \forall i\in\mathcal{I},\ m\in\mathcal{M}$$

$$x^{trans,xdig}_{m} \geq 0 \quad \forall m\in\mathcal{M}$$

$$x^{\neg manure} \geq 0$$

Appendix C. Data

Table C.2
Production costs and biogas yields of the biomass types. The production costs for sugar beet and straw, i.e. without any storage costs etc., as well as transportation costs to the farm are given by Abildgaard (2016). From the field to the farmer, we assume a distance of 1.5 kilometers for sugar beet and 1.9 kilometers for straw. The production cost and biogas yield of manure are from Boldrin et al. (2016). The biogas yield and extra CAPEX and OPEX for sugar beet and straw are from EA Energianalyse (2014).

Biomass type	Production cost and transport to farm (euros per ton)	Biogas yield (normal cubic meters BG per ton)	Extra CAPEX (euros per ton per year)	Extra OPEX (euros per ton)
Sugar beet	23	108.6	0.54	2.41
Manure	6	12.6	0	0
Straw	28	317	4.62	15.41

Table C.1
Data for the case study—input side. OPEX are in euros per ton, 2015 and all CAPEX are annualized with a rate of return of 5% and the given lifetime of the process (20 years are used when no data) and are in euros per ton per year, 2015. All data for sugar beet and manure are from Boldrin et al. (2016). The data for straw are from Abildgaard (2016).

Sugar beet							
Process	CAPEX	OPEX	Min. process time	Max. process time	Efficiency, $\eta_{i,p',p}$	Efficiency, $\eta_{i,p,p}$	Energy efficiency
Storage1	0.25	1.61	1	16	100%	100%	0%
Washer	0	2.57	1	1	100%	100%	0%
Storage2	0.25	1.61	1	4	100%	100%	0%
Cutter	0	2.14	1	1	100%	100%	0%
Ensilage	0.11	1.61	26	52	85%	100%	2%
Storage3	0.25	1.61	1	4	100%	100%	−10%
Manure							
Process	CAPEX	OPEX	Min. process time	Max. process time	Efficiency, $\eta_{i,p',p}$	Efficiency, $\eta_{i,p,p}$	Energy efficiency
Storage1	0.25	0	1	4	100%	100%	0%
Storage2	0.25	0	1	4	100%	100%	0%
Straw							
Process	CAPEX	OPEX	Min. process time	Max. process time	Efficiency, $\eta_{i,p',p}$	Efficiency, $\eta_{i,p,p}$	Energy efficiency
Storage1	1.90	0	1	52	100%	100%	0%
Briquetting	3.88	10.18	1	1	100%	100%	20%
Storage2	0.95	0	1	52	100%	100%	0%

Table C.3
Data for the case study—transportation. All costs are in euros, 2015. Further, the handling price of digestate, $c^{HANDLING,dig_{all}}$, is 0.40 euros per ton. Data for the last radii is kept out for the types where it is not needed due to too large costs etc. The amount of input in each circle for straw as well as transportation costs for all substrates are data from Abildgaard (2016). The amount of input for sugar beet and manure are from Boldrin et al. (2016).

Radius	Sugar beet			Manure			Straw			Digestate		
	$am_{i,n'}$	$\Delta d_{i,n'}$	$c^{TRANS}_{i,m}$	$am_{i,n'}$	$\Delta d_{i,n'}$	$c^{TRANS}_{i,m}$	$am_{i,n'}$	$\Delta d_{i,n'}$	$c^{TRANS}_{i,m}$	$am_{i,n'}$	$\Delta d_{n'}$	$c^{TRANS,dig}_{m}$
5	0	4	0.00	45,089	4	0.81	10,926	4	5.90	14,080	4	0.40
10	1159	8	2.63	166,934	7	1.33	26,094	7	6.91	37,240	7	0.90
15	1545	11	3.12	304,074	10	1.91	24,385	9	8.02	109,521	11	1.45
20	3508	15	3.63	455,056	14	2.49	29,203	12	9.16			
25	4035	18	4.14				39,645	15	10.30			
30	2091	19	4.64				62,513	19	11.44			
35	3687	22	5.15				68,058	23	12.59			
40	4470	26	5.66				73,320	26	13.73			
45	4178	29	6.17				68,590	29	14.88			
50	2493	30	6.69				78,512	32	16.03			
55	4606	34	7.20				68,458	34	17.18			
60	5219	37	7.71				57,728	37	18.33			
65	5643	40	8.22				60,372	39	19.48			
70	4579	43	8.73				78,902	42	20.62			
75	5440	46	9.24				90,134	45	21.77			
80	4933	49	9.75				101,572	49	22.92			
80+	12,414	54	10.00									

Table C.4
Data for the case study – output side (Danish Energy Agency, 2012b; Evald, Hu, & Hansen, 2013; Pizarro, 2014). All costs are in euros, 2015 and all CAPEX's and fixed OPEX's are annualized with a rate of return of 5% and the given lifetime of the process (20 years are used in case of no data). CAPEX and OPEXfix are in euros per normal cubic meter per hour per year and OPEXvar is in euros per normal cubic meter except for Boiler, Single-cycle gas turbine (SCGT), Combined-cycle gas turbine (CCGT), and Gas engine which are in euros per megawatt per year and euros per megawatt hour.

Process	CAPEX	OPEXfix	OPEXvar	Min. process time	Max. process time	Efficiency, $\eta_{p',p}$	Efficiency same, $\eta_{p,p}$	f_p	Main process p
Gas storage	2.35			1	12	100	100		
Ironadsorption	28.25	162.4		1	1	100			
Bio-scrubbing	59.70	32.5		1	1	100			
Bio-thrickling	48.87	8.1		1	1	100			
Water scrubbing	120.36	30		1	1	69.96			
Org. phys. scrubbing	136.41	34		1	1	70.67			
Press. swing absorption	120.36	75		1	1	71.77			
Chem. scrubbin	120.36	45		1	1	70.23			
Methanation	561.70	150.5		1	1	176.8		6.75	Natural gas
Boiler	6107.17	3700		1	1	0.74			
SCGT	42571.47		3.4	1	1	0.62		0.95	Electricity
CCGT	78047.7		2.5	1	1	0.67		1.61	Electricity
Gas engine	120427.86		9.3	1	1	0.69		0.92	Electricity
7to40	57.37	20		1	1	100			
1to40	114.75	40		1	1	100			
Heat storage	46.80	4.07		1	12	100	99.97		
Nm3toMW				0	0	1.08			

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Paper D

Why would biogas plants choose to upgrade?

Why would biogas plants choose to upgrade?

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Abstract

In Denmark it has been possible to upgrade biogas and achieve support as biogas-based heat and power production from 2014. Since then a large share of both new and old biogas production plants has chosen to upgrade the biogas.

We use a mixed integer programming model to find the optimal biogas value chain, and co-operative game theory to understand the real world observations compared to our results. More specifically we apply three profit allocation mechanisms to allocate the total profit between the heterogeneous owners in the value chain. We find, that Danish biogas plants should use a large share of manure combined with deep litter. Furthermore, we find that the input suppliers have a relatively poor bargaining power in the profit allocation negotiations due to poor alternatives. This may explain why livestock farmers tend to achieve a low payment for their input, and also why they may be hesitating to join a supply agreement with a biogas plant.

We find that the preference for upgrading has several reasons. If the natural gas price is expected to be high, it is preferable to upgrade compared to be using biogas directly in a local combined heat and power plant (CHP). With a lower natural gas price, upgrading could be a preferred choice for the biogas plant, since a CHP has better alternatives and therefore a better bargaining power before investments. When the value chain contains an upgrading plant, the biogas plant will have a greater bargaining power—in particular after investments.

Keywords: Cooperative game theory, Profit allocation, Mixed integer programming, Biogas, Biomethane, Renewable energy, Value chain

1. Introduction

The Danish biogas production has developed remarkably the latest years since the change in regulation following the Energy Agreement back in 2012 (Danish Government, 2012), where it was agreed that biogas among other renewables should be strengthened compared to earlier. Several initiatives were started, where probably the most important part was that, after the EU ratification

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in 2014, it became possible to gain support when biogas is upgraded or used directly for industry, transport or in heat and power production(Danish Energy Association, 2013; European Commision, 2013).

The new changes have been a great success, and new biogas plants have been built all over Denmark the latest years (Harder, 2016), in particular the upgrading option have increased the possibility to take advantages of economy of scale independently of local heat demand (Skovsgaard and Jacobsen, 2017). Looking at the latest development and projections for new biogas plants, there is a clear picture of biogas plants choosing to upgrade instead of finding a local source of consumption. This development is both in relation to new plants, but also old biogas plants have chosen to upgrade and not proceed to deliver biogas for a local CHP (Harder, 2016). An explanation for this development could be a lack of heat demand and even a reduced heat demand along with new and cheaper heat production technologies. Furthermore, it could prove more profitable for the biogas plant to choose the upgrading solution independent of the overall optimal solution. This is the hypothesis of this paper, which we will investigate further.

The biogas value chain involves several actors from different sectors, that operate at diverse markets with diverse regulation; and input for biogas production is often a bi-product while biogas is one fuel out of many in the production of energy commodities. This may affect the opportunities for the biogas producers, the optimal pricing between the different actors in the value chain, and maybe also the optimal production decision. Additionally, both input and output prices can be difficult to estimate, as there are no or imperfect markets for both inputs and output. This gives a challenge when profits should be allocated within the value chain.

Variations in ownership structures and potentials for vertical integration is out of scope for this paper. We are however aware that parts of the value chain can be considered as bilateral monopolies after investments; and that this can affect the production level in the value chain. The Myerson-Satterhwaite theorem (Myerson and Satterthwaite, 1983) states, that it is impossible to achieve ex. post efficiency in bilateral trade in cases of private information, and each time two owners stand in front of each other, there is a risk of adverse selection with the wrong design of profit allocation mechanism.

Blair et al. (1989) finds a great disagreement in the literature with regards to finding an optimal solution for the quantity and price between bilateral monopolies, they refer to Bowley (1928), Fellner (1947), and Machlup and Taber (1960) that all have found a joint profit maximizing solution under a variety of assumptions. Blair et al. (1989) concludes that the social optimal solution only can be found with joint profit optimization, and that the price between the parties is a way to share the maximized profit. Truett and Truett (1993) takes the step further and proved that under particular circumstances, hereunder perfect information, there will be only one stable and theoretically optimal price for the intermediate products between the two monopolies. This price would among other things depend on bargaining power between the two monopolies.

Within the cooperative game theoretic literature several (cost) allocation mechanisms are presented and tested both theoretically, e.g. (Tijs, 1986; Schmeidler, 1969; Megiddo, 1978; McCain, 2008; Hougaard, 2009) and empirically (Massol and Tchung-Ming, 2010; Frisk et al., 2010; Lozano et al., 2013; Nagarajan and Sošić, 2008). However, most of the literature is focused on homogeneous producer types with slightly different properties; this could be a cooperative of pig producers who slaughtered and sold the pigs together (Bogetoft and Olesen, 2007), a cooperation among liquefied natural gas suppliers (Massol and Tchung-Ming, 2010), or a cooperation of wood suppliers (Frisk et al., 2010). We will apply some of the payment schemes presented in the literature on the non-homogeneous owners in the biogas value chain. This has to our knowledge not previously been done.

In this paper we will not try to find one optimal price between the owners, and as already mentioned we will not investigate different ownership structures. Instead we will use a value chain optimisation model (Jensen et al., 2017) in order to see the potential profits which can be gained in the optimal biogas value chain under perfect information and to find the optimal biogas value chain design - which inputs are best and what is the best choice of energy converter under a specific set of assumptions, presented in chapter 2, this we do in chapter 4.

Drawing on *cooperative game theory* (McCain, 2008; Gibbons, 1992), *cost- and profit allocation theory* (Hougaard, 2009; Bogetoft and Olesen, 2007) and *principal-agent theory* (Mas-Colell, Andreu; Whinston, Michael D.; Green, 1995), we consider how a proper profit allocation mechanism could help to reach a relevant value chain design for non-homogeneous owners, and we discuss why the optimal design may not always be the preferred design. We discuss this in chapter 5 based on the theory presented in chapter 3.

2. How we find the optimal choice of value chain

In this chapter we follow the track of Blair et al. (1989) and consider a situation with joint profit optimization assuming perfect information between the owners.

The biogas value chain consists of several separate owners, o, who often operates on other markets in different sectors. The biogas value chain is depicted in figure 1 and the group of owners, $\mathcal{O}$, are in this paper defined as the livestock farmers, the substrate farmers, the plant and the energy converters. These parties delivers input and/or are involved directly in the biogas production and conversion process. Only the plant, and maybe in some cases the biogas upgrading facility, has biogas production as the primary purpose, whereas the farmers focus on the highly competitive agricultural sector. The energy converter, in the end of the value chain, focus on the end product; biomethane (upgraded biogas), electricity and/or heat. While the electricity and gas markets are exposed to a high level of competition, heat production can be considered as a natural monopoly, and is therefore monopoly regulated. As will be presented in section 2.1, the regulative design implies, that the biogas plant is highly dependent on waste input—in this paper defined as agricultural waste—in order to be *allowed* to receive support, and a demand from the energy converter in order to *receive* support. Both sectors are highly exposed to competition or is monopoly regulated.

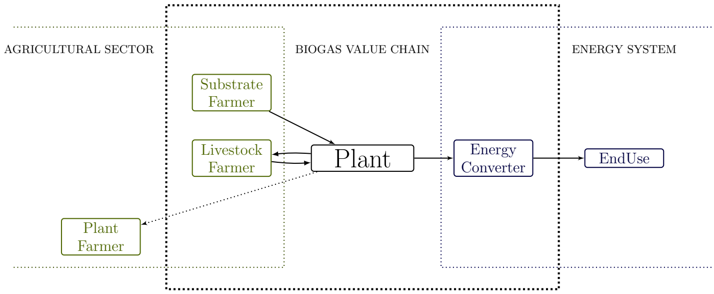

Figure 1: Ownership structure

The ownership structure within the value chain differs among plants, and in Denmark you find several variations. In one case, a group of farmers have invested in a biogas plant and an upgrading facility, e.g. Madsen Bioenergi (Madsen Bioenergi, 2017). In another case, one owner controls input and biogas production, while another owner controls the upgrading plant, e.g. Fredericia waste water (Wittrup, 2010). The specific choice of ownership structure depend on several factors hereunder cost of capital. As mentioned, this will not be a study on the optimal ownership structure and therefore not investigated further.

Instead, we focus on the optimal choice of value chain design by using the plant level model presented in section 2.2, that includes the basic assumptions presented in 2.3 and most of the regulation around the value chain. The regulation also influences on the choice of value chain design and is presented below.

2.1. Regulation

Focus in Danish biogas regulation span over several sectors and different priorities. Biogas support and the regulative set-up around biogas is designed in an energy focused mindset, while emphasis at the same time has been put on the need of sustainability and use of manure in the biogas production. These two focal points surround the Danish biogas policy and has a significant influence on the importance of the separate owners in the value chain

Two overall parts of the biogas regulation is presented in this section, and further described in Appendix A.

- Input: In order to receive biogas support, it is important, that a large share of the input in the biogas production consists of waste—preferable manure or waste water. This could also be waste products from slaughterhouses or dairy production, however these sources are limited. Alternatively, the biogas production can be supplemented with other waste products

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such as straw or deep litter. Furthermore, it is allowed to use a limited amount of energy crops.

- Output: Biogas support is primarily paid in the end of the value chain, i.e. to the energy converter. The energy converter can be an upgrading plant, a CHP, a heat producer, industry or transport.

From this we identify three overall parties in the biogas value chain, that are necessary to include in order to receive support with the current regulatory setting; the livestock farmer, the biogas plant and the energy converter.

The regulation with regards to energy production and consumption is extensive in Denmark, where the general principles are that renewable energy is supported, and taxed as little as possible, while electricity and fossil fuels are taxed heavily with few exceptions. A further description with regards to biogas production can be found in Appendix A.

A large share of the heat supply in Denmark is covered by local heat production plants and distributed through a local grid. These are natural monopolies and therefore monopoly regulated. The regulation type is a cost-of-service-regulation, where profits for the producers should be zero (*hvile-i-sig-selv* in Danish). The principle is, that only heat production *costs* are covered by the consumer, who often is a co-owner. In order to assure as low costs for the heat consumers as possible, the heat producers are obliged to produce heat at the lowest possible costs, and this is monitored by the Danish Energy Regulatory Authority (DERA). One of the implications of this regulation is that profit allocation within the biogas value chain can be affected by the regulation, if the energy converter produces heat.

2.2. Plant level model

The model takes as a starting point the model from Jensen et al. (2017), where a mathematical optimisation model for the biogas supply chain was presented. The aim of the model is to find the optimal choice of the chain from the farmer to the energy demand by finding the optimal choice of e.g. inputs to the plant and technologies for utilising the biogas. The modelled chain can be seen in figure 2. The supply chain is modelled such that the input side, i.e. until the plant, uses a weekly time scale, while the output side uses an hourly time scale. This allows us to capture the fluctuations of energy prices and still keeping the model as small as possible. The model combines both the strategic decision of sizing the processes, and tactical decisions, e.g. amount of manure used as input, when to store the biogas, etc.

The possible energy converters in the chain are a combined heat and power plant, a heat boiler, an upgrading plant, and upgrading through methanation. A traditional upgrading plant removes the CO_2 from the biogas such that the methane content of the resulting biomethane will be similar to that of natural gas. For methanation, hydrogen is produced through electrolysis and added such that the CO_2 from the biogas is converted to methane. Besides the added amount of biomethane from the methanation process compared to the traditional upgrading plant, process heat will also be generated of which some can be sold for district heating.

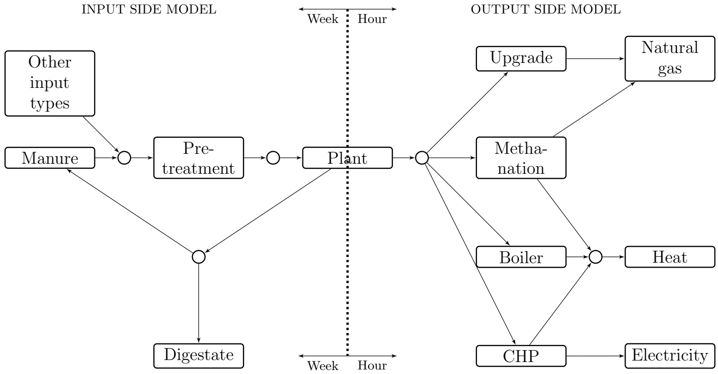

Figure 2: The biogas value chain from farmer to energy demand with the input side using a weekly time scale and the output side using an hourly time scale.

The objective function used in (Jensen et al., 2017) was profit maximisation. In this paper, the objective function is slightly different. In (Jensen et al., 2017), the farmer was only included by receiving a price for the delivered manure or crops. In this paper, the farmer is a potential owner and his costs must therefore be included in the total costs of the chain. For practical reasons related to profit allocation, see subsection 3.3, it was decided to move the transportation costs of the biomasses to the biomass producer instead of the biogas plant. To include ownership in the model, we have included a new set of constraints to run the model with in order to see this effect, which are described in equation 1–5. We identified two more neccessary constraints that were not in the model from Jensen et al. (2017). These are given in constraints 6 and 7.

The objective function is now to maximise the sum of profit for the owners:

$$Max \sum_{o \in \mathcal{O}} \pi_o \tag{1}$$

Where π_o is the profit for each owner, o, in the project and is given by:

$$\pi_o = INC_o - C_o \quad \forall o \in \mathcal{O} \tag{2}$$

Where INC_o and C_o are the income and cost for each owner in the project. The income for each owner is described by:

$$INC_o = \sum_{\substack{v=(p,t)\in\\ \overline{\mathcal{V}}^E \cap (\overline{\mathcal{P}}^E \times \overline{\mathcal{T}})\\ |\mathcal{OP}(o,p)}} \Big(\sum_{a\in\overline{\mathcal{A}}^-(v)} (\overline{x}_a - x^{left}_{p,t})\, \eta^{price}_a\, \overline{\rho}_{p,t}\, \eta^{available} \tag{3a}$$

$$+ \rho^{support}_o + \sum_{\substack{p\in\mathcal{P}^{plant}\\ |\mathcal{OP}(o,p)}} x^{\neg manure}\, \rho^{dig} \qquad \forall o \in \mathcal{O} \tag{3b}$$

Here line 3a is the income from selling the energy. This is only earned if owner o owns the end process as given by the set $\mathcal{OP}(o,p)$. The amount produced on the arc a, $\overline{x}_a$, is reduced by the amount that cannot be sold, which is only relevant for heat as the heat demand is the limiting factor. Then the result is multiplied by a price parameter, η^{price}_a, which reduces the price obtained. This reduction is only applied when biomethane is produced to reflect the heating value of the produced biomethane compared to that of natural gas. Last, we multiply with the price of the end product, $\overline{\rho}_{p,t}$, and an expected percentage of which the production can occur, $\eta^{available}$. Line 3b is the amount of support received by owner o, $\rho^{support}_o$, and the income, ρ^{dig}, from selling the digestate, which cannot be send back to the livestock farmers, $x^{\neg manure}$.

The cost is given by:

$$C_o = \sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}\cap(\mathcal{I}\times\mathcal{P}\times\mathcal{T}\times\mathcal{E})\\ |\mathcal{OP}(o,p)}} \sum_{a\in\mathcal{A}^-(v)} x_a\, (c^{OPEX}_{i,p} + c^{OPEX,var}_{i,p,t}) + \sum_{\substack{v=(p,t)\in\\ \overline{\mathcal{V}}\cap(\overline{\mathcal{P}}\times\overline{\mathcal{T}})\\ |\mathcal{OP}(o,p)}} \sum_{a\in\overline{\mathcal{A}}^-(v)} \overline{x}_a\, (\overline{c}^{OPEX}_p + \overline{c}^{OPEX,var}_{p,t}) \tag{4a}$$

$$+ \sum_{i\in\mathcal{I}} \sum_{\substack{p\in\mathcal{P}\\ |\mathcal{OP}(o,p)}} k_{i,p}\, \frac{T}{t^{min}_{i,p}}\, c^{CAPEX}_{i,p} + \sum_{\substack{p\in\overline{\mathcal{P}}\\ |\mathcal{OP}(o,p)}} \overline{k}_p\, \overline{c}^{CAPEX}_p \tag{4b}$$

$$+ \sum_{\substack{p\in\mathcal{P}^{plant}\\ |\mathcal{OP}(o,p)}} \Big(\sum_{n\in\mathcal{N}} x^{SOS2}_n\, c^{OPEX,SOS2}_n + \sum_{n\in\mathcal{N}} k^{SOS2}_n\, c^{CAPEX,SOS2}_n \qquad \forall o \in \mathcal{O} \tag{4c}$$

$$+ \sum_{m\in\mathcal{M}} x^{trans,xdig}_m\, c^{TRANS,xdig}_m + \sum_{v\in\mathcal{V}^P} \sum_{a\in\mathcal{A}^-(v)} (x_a\, \eta^{plant} - x^{\neg manure})\, c^{HANDLING,dig} \Big) \tag{4d}$$

$$+ \sum_{\substack{i\in\mathcal{I}\\ |\mathcal{IO}(i,o)}} \sum_{m\in\mathcal{M}} x^{trans}_{i,m}\, c^{TRANS}_{i,m} + \sum_{\substack{p\in\overline{\mathcal{P}}^{heat}\\ |\mathcal{OP}(o,p)}} \overline{x}^{heattax} + \sum_{\substack{p\in\mathcal{P}^{slurry}\\ |\mathcal{OP}(o,p)}} x^{should}\, \rho^{dig} \tag{4e}$$

Line 4a and 4b are the OPEX and CAPEX of each process and is added to the cost of the owner if he owns the process as defined by the set $\mathcal{OP}(o,p)$. Line 4c-4d is the OPEX and CAPEX of the plant and the transportation and handling costs of digestate. Line 4e contains three elements. First, the transportation cost of all biomasses, which must be paid by the producer of the biomass as defined by the set $\mathcal{IO}(i,o)$. Second, the tax on excess heat delivery to the district heating network is added

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for the owner of the heat process. This is only relevant in the case of methanation where heat is generated as excess heat. In the model from Jensen et al. (2017), heat tax was not included. The primary reason for livestock farmers to send their manure to a biogas plant is the gains of having their manure treated and thereby a better fertiliser. If the livestock farmers do not receive the digestate, it represents a loss in the value chain corresponding to the digestate value, ρ^{dig}. This cost is added as the final element in line 4e.

The livestock farmers may take up to a certain percentage of the digestate, γ. The amount that is not sent back to the livestock farmer but should have been, according to the amount he is willing to take, can be calculated as:

$$x^{should} \geq \sum_{v \in \mathcal{V}^M} \sum_{a \in \mathcal{A}^+(v)} x_a \gamma - \Big(\sum_{\substack{v=(i,p,t,e) \in \\ \mathcal{V}^P \cap (\mathcal{P}^P \times \mathcal{T} \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} x_a \eta^{plant} - x^{\neg manure} \Big) \tag{5}$$

Where the first term on the right hand side represents the amount the farmer is willing to take, and the second term is the amount of available digestate minus the amount of digestate sent elsewhere.

The heat tax is the amount of heat generated and delivered to the heat demand, $p' \in \overline{\mathcal{P}}^H$, from the methanation process $p \in \overline{\mathcal{P}}^{m^3}$, i.e. excluding the heat produced which cannot be sent to the demand, $x^{left}_{p',t}$. The total heat tax is calculated by the following equation:

$$x^{heattax} \geq c^{tax}_{p,p'} \Big(\Big(\sum_{v=(p,t) \overline{\mathcal{V}} \cap (\overline{\mathcal{P}}^{m^3} \times \mathcal{T})} \sum_{a \in \overline{\mathcal{A}}^+(v)} \overline{x}_a \Big) - \sum_{t \in \overline{\mathcal{T}}} x^{left}_{p',t} \Big) \quad \forall p \in \overline{\mathcal{P}}^{m^3}, p' \in \overline{\mathcal{P}}^H \tag{6}$$

In the model from Jensen et al. (2017), the amount of dry matter allowed in the total mix was not modelled. However, this is necessary to consider the problems obtained by the biogas plants as the dry matter content of inputs differs significantly and there is a limit on the total dry matter content of the mix. Therefore, we add another constraint that sets a limit on the dry matter content of the input mix by using the allowed dry matter content of the input mix, Γ^{DM}, and the dry matter content of each input, γ_i^{DM}. The constraint is given by:

$$\sum_{\substack{v=(i,p,t,e) \in \\ \mathcal{V}^P \cap (\mathcal{I} \times \mathcal{P}^P \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} \gamma_i^{DM} x_a \leq \Gamma^{DM} \sum_{\substack{v=(i,p,t,e) \in \mathcal{V}^P \\ \cap (\mathcal{I} \times \mathcal{P}^P \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} x_a \qquad \forall t \in \mathcal{T} \tag{7}$$

2.3. Assumptions

In our calculations we follow the recommendations for socio-economic analysis for Denmark with an interest rate of 4% for all capital expenditures (CAPEX) (Danish Energy Agency, 2013) and the depreciation time is set according to the data sources. If no data was available, we used a depreciation time of 20 years. Data on input and output process costs can be found in Appendix B, Table B.3 and B.6, where we also present a graph on the overall CAPEX used in the model,

Figure B.1. We assume economy of scale for the biogas plant, and constant return to scale with regards to the upgrading plants and pretreatment of substrates.

We assume that the farmers cover transportation costs to and from the plant. Data for transportation can be found in Appendix B, Table B.5. We also assume that the pretreatment of straw and deep litter is undertaken at the biogas plant, while the ensilage of maize and washing of the sugar beets is done by the farmer. The cutting and ensilage of sugar beets is done by the plant. For input to the plant, we set a maximum dry matter content of the total feedstock to be 13% (Jørgensen, 2013). Data for the input can be found in Appendix B, Table B.4. We assume that excess digestate can be sold for 8.85 €/tonnes and must be transported with the costs given in Appendix B, Table B.5.

The geographical position of the plant is in North West Denmark. This placement has the advantage of being close to a vast amount of manure and other substrates. A potential disadvantage of the area is a lot of other biogas plants, who would be interested in the same substrates, combined with a relatively low heat demand. We assume, that the model plant can be relatively certain of a demand from the local heat plant in the town *Vinderup*, which corresponds to approximately 36,000 MWh/year (Vinderup Kraftvarmeværk, 2014). This is the heat demand we use in the model. The heat price is set individually at each plant following the principle of cost-of-service described in section 2.1. The heat price has a large variation across the country so we use the heat price set by *Vinderup Kraftvarmeværk* as given by Danish Energy Regulatory Authorities, see (Energitilsynet, 2017).

2016 is the base year for our model year, meaning that all prices for power, heat, and natural gas are from 2016 and so are the regulatory tariffs. The power price is from the Nordpool Spot market, which is the trading place for the Nordic power market; while the natural gas is traded on GasPointNordic and the prices we use are the historic prices from 2016. An overview of the historical prices can be seen in figure 3. We apply the regulation given in Appendix A, Table A.1 and Table A.2.

3. Method to allocate profit

In section 4 we confirm the results from (Skovsgaard and Jacobsen, 2017) and (Jensen et al., 2017), that biogas production can be profitable with the current regulation; however, the value chain can be fragile without a proper profit allocation between the owners.

A basic principle for profit allocation could be to at least ensure feasibility for all participating owners in the value chain—meaning that profit should be greater than zero. This may not be enough, so in order to follow the idea from Blair et al. (1989) to find a way to share maximised profit, we use the overall principles from cooperative game theory with regard to cost allocation, and we focus on the fairness criteria *equality* and *individual rationality.* Our aim is *not* to identify the optimal allocation mechanism, as this can not be decided from a theoretical study (Tijs, 1986)

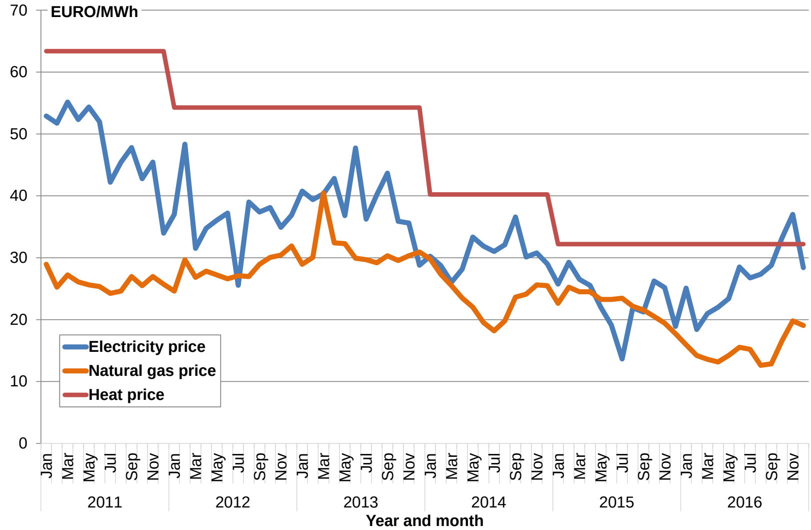

Figure 3: The historical prices for electricity, natural gas, and heat

and (Bogetoft and Olesen, 2007). Rather we try to understand the strategic considerations related to profit allocation and the following choices made by the owners, when the value chain design is made.

To make this assessment, we investigate three allocation mechanisms suited for the value chain, where profits are distributed through the prices in the chain. These mechanisms are:

- Full equality, that resembles the egalitarian cost allocation method presented in e.g. (Tijs, 1986)
- Proportionality, in cost allocation theory also presented as AVC (Average cost rule) (Hougaard, 2009)
- Individual rationality, inspired by the nucleolus as in e.g. (Massol and Tchung-Ming, 2010)

In section 3.3, we present how the profit allocation is modelled.

Before we continue the considerations with regards to profit allocation, we limit the cooperative to the absolute necessary owners in the value chain, assuming that the value chain prefers to keep the subsidies presented in section 2.1. These owners are the livestock farmer (no waste, no support), the plant (no plant, no biogas) and the energy converter (no energy converter, no support). This leaves out the substrate farmer, who will not be included in the cooperative, because support *can* be achieved without additional substrates, and substrates can be substituted. Instead, the substrate farmer is paid an amount for the substrate corresponding to the production costs for the substrate transported to the plant plus additionally 10% of the transportation costs. We are aware that there are other ways of determining the price, see e.g. (Giannoccaro et al., 2017), handling the availability based on the price of biomasses in a region, see e.g. (Bai et al., 2012), and that 10% for some substrates is too little, but this has not been the main focus of this paper.

3.1. Considerations for the choice of allocation

Several relevant fairness criteria for an allocation mechanism are presented in the literature. Bogetoft and Olesen (2007) presents a long list of potentially relevant criteria depending on the type of cooperative and the closest surroundings of the cooperative, e.g. the cooperative could be a group of pig farmers, who can affect the market prices for pigs. In this case it would be relevant to design the allocation mechanism to include an incentive for not producing too many pigs, and thereby drive the market prices down (Bogetoft and Olesen, 2007). Others present the fairness criteria at a more general level e.g. (Tijs, 1986; Hougaard, 2009).

As mentioned we focus on the fairness criteria: equality and individual rationality. These properties are considered in most cooperative game theoretic literature related to (cost) allocation see e.g. (Tijs, 1986; Bogetoft and Olesen, 2007; Frisk et al., 2010; Schmeidler, 1969; Megiddo, 1978; Hougaard, 2009). Other fairness criteria such as risks for the value chain and the risk of adverse selection are also considered.

Equality can be interpreted in many ways. Denmark has a long tradition for cooperative movements in the agricultural sector, and "one man—one vote" was a general principle in these cooperatives. Non-cooperative game theory follows the hypothesis, that the rational agent in a one shot ultimatum game (also known as the "split the pie game" (Gibbons, 1992)) would offer the other agent a zero share of the pie, which a rational agent would accept. Several empirical studies show, that most people does *not* take the entire cake, and if they do the other part would retaliate and not accept the offer. McCain (2008) presents this as an argument for including social norms and reciprocity motives into the cooperative game theory and thereby get closer to the empirical findings. Hougaard (2009) argues that equality in some form, e.g. direct equality or maximin equality, can be found in most large religions and thereby social norms. We therefore consider this fairness criteria as crucial for our evaluation of the allocation mechanisms.

Another important element of *homo economicus* is individual rationality: "Does it make sense to join in? Or is there a better alternative?", we have therefore chosen to use individual rationality as the other fairness criteria to focus on. We present this further in section 3.4.

3.2. Payment schemes

Several allocation mechanisms have been found and compared within cooperatives with homogeneous owners. There is e.g. the proportional allocation, where profit is allocated: in accordance with cost (Equal return on capital) (Hougaard, 2009); according to the gain delivered to the cooperative (ACA) (Bogetoft and Olesen, 2007); or by using the Shapley Value, where each part in the cooperative gains a profit corresponding to the gain, that the part has contributed with (Lemaire, 1984; Massol and Tchung-Ming, 2010; Frisk et al., 2010). Other payment schemes focus on the egalitarian principle such as the egalitarian method, where profit is divided equally between all parties in the cooperative (Tijs, 1986; Lemaire, 1984; Massol and Tchung-Ming, 2010), or the nucleolus payment scheme, where the profit allocation depend on the alternative profit of the marginal participant (Massol and Tchung-Ming, 2010; Schmeidler, 1969; Frisk et al., 2010). Many of these allocation mechanisms could be relevant for a payment scheme between livestock farmers in a cooperative delivering manure to the biogas plant. In such a cooperative the producers would be homogeneous with slightly different properties, such as distance from the plant and content of dry matter in the manure, and a good allocation scheme would include incentives to deliver a high dry matter content.

An overall assumption in this paper is, that there is some kind of cooperative among the livestock farmers where all these mechanisms could be relevant, it is however not the focus point here. Instead we focus on the three overall owners in the value chain (livestock farmers, plant and energy converters), who are heterogeneous producer types with a large degree of interdependency. This implies that each party is as relevant as the other, even though one of the parties may take the initiative and by that may gain an upper-hand in the negotiations. We imagine, this could be the plant that only exists with the purpose of producing biogas, whereas biogas is a secondary product for the farmer, and for the energy converter the purpose is to produce a specific type of energy.

In this context, many of the above mentioned allocation schemes become irrelevant, however some of the principles from these schemes can be reused. In section 3.3, relevant versions of the egalitarian method, the proportionality principle, and a method inspired by the nucleolus—here called individual rationality—are presented.

3.3. Modelling the allocation mechanisms

After running the plant level model, the allocation is performed. A general allocation model is given below, where constraint 9 is mechanism specific and will be given for each of the used allocation mechanisms described in the following sections.

$$\begin{aligned}
&\text{Max} \quad z = \lambda && && (8)\\
&\text{S.t.} \quad \textbf{Feasibility constraint} && \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} && (9)\\
&\pi_o^{CA} = \gamma^{feas} C_o^* && \forall o \in \mathcal{O}^{sub} && (10)\\
&\pi_o^{CA} = \pi_o^* - \sum_{o' \in \mathcal{OTO}(o',o)} \rho_{o',o}^{CA} + \sum_{o' \in \mathcal{OTO}(o,o')} \rho_{o,o'}^{CA} && \forall o \in \mathcal{O} && (11)\\
&\lambda \geq 0 && && (12)\\
&\pi_o^{CA} \geq 0 && \forall o \in \mathcal{O} && (13)\\
&\rho_{o,o'}^{CA} \geq 0 && \forall o \in \mathcal{O}, o' \in \mathcal{OTO}(o,o') && (14)
\end{aligned}$$

The objective function 8 is to maximise the decision variable λ, which is specific for each of the used allocation mechanisms. Constraint 10 sets the profit of each of the substrate owners equal to a parameter, γ^{feas}, representing the percentage of its costs from the plant level model, C_o^*, that should be covered. In constraint 11, the profit for each owner using the cost allocation method, π_o^{CA}, is calculated as the profit obtained from the plant level model, π_o^*, minus the price paid for buying input to the process plus the price obtained from selling the output from the owner.

3.3.1. Full Equality, direct equality

The Full Equality method has many names, e.g. the egalitarian method, direct equality etc. The principle is that all owners share the total profit equally; irrespective of their total costs.

The feasibility constraint for the full equality allocation is:

$$\pi_o^{CA} = \frac{1}{|o \in \mathcal{O} \setminus \mathcal{O}^{sub}|} \sum_{o' \in \mathcal{O} \setminus \mathcal{O}^{sub}} \pi_{o'}^{CA} \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} \qquad (15)$$

Here the profit of each owner who are not substrate owners, will be a share of the total profit for all non-substrate owners. The share relies on the number of non-substrate owners and is therefore divided by the number of non-substrate owners. For this allocation, λ is not used in the feasibility constraint. This means that there is no upper bound on λ and the problem gets unbounded. To avoid this, we simply set $\lambda = 0$.

An owner with a high cost would bear the highest risk using this mechanism, which most likely would not be considered fair. Furthermore, there is a minor challenge with adverse selection as full equality requires all owners to report their cost honestly, which implies a risk that an owner would report a higher cost than what he actually faces in order to keep some profit for himself.

3.3.2. Proportionality

The proportionality mechanism is not as simple as full equality. One must determine what element the profit should be proportional to, e.g. total costs, CAPEX or OPEX. Looking at the three primary parts of the value chain, livestock farmer, plant and energy converter, it becomes difficult to find one common parameter or variable that counts for all parts of the value chain and still doesn't give a challenge in relation to knowledge-sharing. In this paper, we choose to use the cost for each owner from the plant level model. This choice implies that all owners should have a cost assigned and this is why we have chosen to add the transport cost to the farmers unlike in the model from (Jensen et al., 2017).

The feasibility constraint for the proportionality allocation is:

$$\pi_o^{CA} = \lambda C_o^* \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} \tag{16}$$

Here λ will be the percentage of the cost that can be covered for each of the non-substrate owners.

The proportionality mechanism suffers from adverse selection to an even higher degree, as it gives an incentive to boost your own costs in order the achieve a higher share of the total profits. The method does not reflect, that all three parts of the chain are necessary to achieve support.

3.3.3. Individual rationality, maximin equality

The last mechanism that we apply is inspired by the maximin profit allocation, nucleolus. In the traditional nucleolus all combinations of participating owners and their alternative profits are used in the allocation, and profit for each owner is found by maximising the distance from the obtained profit to the alternative profit for all subsets of the participating owners. The owners in the traditional nucleolus are of the same type, see e.g. (Frisk et al., 2010), and the operability of the collaboration would therefore not be relying on each owner individually. In our case the owners are relying on each other to make the biogas chain running and the nucleolus can therefore not be directly applied.

Instead of looking at all subsets of the chain, we therefore maximise the distance from the obtained profit to the alternative profit that the owner would get by not participating. This ensures that the obtained solution is within the core, meaning that all owners are better of when they are part of the chain.

The feasibility constraint for the individual rationality cost allocation is:

$$\pi_o^{CA} - \pi_o^{ALT} \geq \lambda \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} \tag{17}$$

Here λ is the gain from participating for all of the non-substrate owners, and π_o^{ALT} is the reported alternative profit for each owner o.

This allocation mechanism can seem more fair, as it is more equal, than the proportional distribution and takes more individual properties into account than the full equality distribution, however costs are not directly taken into consideration. Other challenges are the lack of transparency and a necessary high level of information in order to calculate the allocation; the last point opens up for dishonest reporting on the best alternative.

We do not know which allocation mechanism is used in the actual biogas value chain, and this would off course also depend on the ownership structure within the specific value chain. In chapter 5 we evaluate the results from the model and relate these results to individual rationality. We then assess the potential implications of this with regard to a possible preferred choice of value chain and profit allocation design.

3.4. Individual rationality

Truett and Truett (1993) argues that one specific price between two parties can be found, and the bargaining power between the two parties contribute in determining this price. But what determines the bargaining power? This—among other things—can depend on the level of information between the parties in the value chain (Radhakrishnan and Srinidhi, 2005) and maybe more importantly by how dependent each party is on the collaboration, which again is determined on the best alternative for each party. This is also highly relevant with regards to profit allocation, and is often referred to as the stand-alone profit. The allocation mechanism is unstable, if the profit allocated to an individual part in the group is below her stand alone profit. Furthermore, a profit allocation is stable if it is *within the core*, where the core is a set of profit allocations, where it is beneficial for all group members to cooperate, meaning that the profit allocation should result in a profit that exceeds the stand-alone profit for all in the cooperative (Bogetoft and Olesen, 2007).

The sample space of best alternatives is quite large, so in order to narrow this sample space down to a reasonable amount of calculations, we exploit that we have reduced the owner group to three overall parties, who are all necessary in order to make a profit. Some of the owners can to some extent be replaced after investments, though at the expense of the overall profit in the value chain.

Our approach is to consider the alternatives for the individual owners and the entire value chain. As capital costs are an extensive part of total costs in a biogas value chain, we both consider the choices before investments and after investments, as the after investment bargaining power might affect the preferences of each owner with regards to both the value chain configuration and the preferred allocation mechanisms before investments.

	Before investments	**After investments**
Livestock farmer	deliver manure to another biogas plant	deliver manure to another biogas plant
Substrate farmer	not deliver the substrate to a biogas plant	find another place to deliver the substrate
Plant	invest capital with 4% interest rate	sunk cost
Energy converter, CHP	biomass based heat boiler	sunk cost and biomass based heat boiler
Energy converter, upgrade	invest capital with 4% interest rate	sunk cost

Table 1: Stand-Alone profits

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The alternatives we evaluate in chapter 5 are presented in table 1, and the results for the table—presented in table 5—are also used in the calculation of the individual rationality profit allocation. For the livestock farmer we assume that the best alternative is to deliver manure at another biogas plant. He could also choose to apply his manure directly on the fields, but this would not give the additional fertiliser value from the digestate. A common payment for manure is, that the biogas plant collect the manure and bring the digestate for free, in table 5 this alternative is presented as a zero profit, as the fertilizer value is not included in the calculations.

The alternatives for the substrate farmer, depends on the substrate. In the case of deep litter, the substrate would most often be considered a waste product. In the case of straw, the farmer might leave the straw on the field or sell it to a local CHP or an ethanol plant.

The plant would have several options, but in this analysis we assume that the plant invests the capital in safe investments at a interest rate corresponding to the socio-economic interest rate before investments, and sunk cost after investment. It is just as likely that the plant would try out other options in particular after investments have been made. We choose this simple alternative, as the more likely alternatives are presented in table 2 on the alternatives for the entire value chain.

In order to decide the best alternatives for the energy converter, we need to make some overall assumptions for the coverage of heat and power demand and realistic options around and within the model. The plant level model presented in chapter 2 can choose between different upgrading technologies, a heat- and power plant (CHP) and a heat boiler. With the current regulation it is unlikely that the optimal choice is to produce heat on biogas. We therefore do not consider this when constructing the table. With regards to the coverage of heat and power demand, we have two different markets to consider. The power market is highly competitive in Denmark, and a CHP is in many cases only viable in relation to a supported fuel as biogas. Heat is monopoly regulated and we assume that the energy converter in most cases will have to find an alternative to the heat production, if the biogas based CHP is dismissed. We therefore assume, that the best alternative to a biogas-based CHP would be a biomass-based heat boiler. This goes for both before and after investments. In the case of upgrading, we assume that the energy converter can freely choose between supplying the heat demand or not.

	Before investments	**After investments**
Livestock farmer	Longer transport distance	Longer transport distance
Substrate farmer	Other substrate	Other substrate and sunk cost in pre-treatment
Energy converter	Other energy converter	Other energy converter and new investments

Table 2: Alternative profits for the value chain, when an owner retracts

The overall principle for alternatives in the value chain is that the plant cannot be substituted, if the value chain should remain. This gives the plant another position with regards to the bargaining power. We assume that all the other parties can be substituted at the expense of total profit in the value chain.

The content of the table is derived through the plant level model. In the case of the livestock farmer, we take advantage of the assumption that the livestock farmer is a cooperative and not a single farmer. It is therefore realistic that some farmers in the cooperative could decide to go for another alternative and not join the value chain. In order to choose a simple case we assume, that one third of the manure at each distance radius leaves the livestock farmer cooperative. The new data on manure access are then fed into the model, and a new optimum is found with a lower profit.

In the case of the substrate farmer and energy converter, the model is run first with the restriction of *not* to choose the optimal choice of substrate. Afterwards the model is run without restriction on the substrate, but with a restriction on the optimal energy converter. We then find the new optimal solution and the corresponding alternative profits.

4. The optimal choice of value chain

4.1. Scenarios

In this section we consider a base scenario, where the model determines the optimal size of the plant, the optimal substrates to add in the production, and the optimal energy converter—given the substrate, transportation, and investment costs in relation to potential income.

The plant level model is a very detailed model, that finds the optimal plant set up considering a large spectrum of choices with regards to substrate inputs (price, investment costs, distances), plant size options (with regard to input options, energy demand and economy of scale) and energy conversion (with regard to biogas output, energy demand and investment and operational costs). All this is optimised together, and in order to keep calculation time down, the optimisation is done for one year, where investment costs are estimated as yearly costs. Therefore, the model does not consider price and cost variations over several years. As energy prices on both the input and output side has great influence on the optimal investment choice and these prices can vary significantly, we run two rounds of sensitivity analysis:

- Sensitivity, where one parameter is changed
- Sensitivity, where a group of parameters are changed

First, we consider the electricity costs that can have great influence on whether it is profitable to use the methanation technology. A large part of the electricity costs in Denmark are energy taxes and fees. In the case of process usage as we assume methanation is, taxes and fees will consist mostly of the Public Service Obligation (PSO). Since the PSO will be phased out until 2022 (The Danish Ministry of Energy, Utilities and Climate, 2016), we find it relevant to see whether it would affect the optimal solution. Therefore we make a scenario where the PSO is set to zero. This scenario is called *PSO zero*.

Another relevant parameter is the natural gas price. The natural gas price was quite low in our base year compared to the previous years, so the optimal solution might change with the natural gas price. We therefore use the time series for the natural gas price from 2013—where the prices were almost the double of the prices in 2016—and see the effect of natural gas prices. In the scenario *NG high* we use the natural gas price and set all other data equal to those of the base scenario.

	Electricity cost		**NG-price**		**Heat price**	
Scenario	Average €/MWh	Level	Average €/MWh	Level	€/MWh	Level
Base	26.5	High	15.2	Low	32.2	Low
PSO zero	15.1	Low	15.2	Low	32.2	Low
NG high	26.5	High	31.4	High	32.2	Low
2015	22.6	Mid	22.3	Mid	32.2	Low
2013	24.0	Semi-High	31.4	High	54.3	High

Table 3: Investigated scenarios

The energy system is to a high extent interrelated: when natural gas prices are high one can expect that this will be reflected in the heat prices in the areas, where natural gas is used as fuel. As Denmark becomes more dependent on renewable energy as wind, solar, and hydro power it can be expected, that the electricity price is less dependent on the natural gas price—except when the renewables are insufficient to cover the electricity demand. We therefore expect less convergence between the natural gas price and electricity costs, however, due to variations in weather conditions we can also expect a certain variation in the electricity price. In the second group of scenarios *2013* and *2015* we test the model with regards to a group of energy costs and prices. In these scenarios we use the fundamental costs from the base-scenario, but use the electricity price + taxes and fees, the natural gas price and the heat price from the years 2013 and 2015.

4.2. Results and preliminary conclusion

The results from the plant level model is seen in Table 4. The biogas plant is as large as possible in all scenarios, 600,000 tonnes per year, and the preferred substrate is in all cases deep litter. In the base scenario a combined heat and power plant is installed. The type of energy converter installed seems to depend mainly on the natural gas price, as the PSO zero scenario still gives us a combined heat and power plant as energy converter, while methanation is preferred in cases with a higher natural gas price. In the scenarios with a higher natural gas price, the total profit also shows to be larger than in the base case.

The amount of support given in each scenario also depends on the energy converter. Here it shows that the given support is lowest in the base scenario, however, the support given per unit of energy is lower when using methanation. In the scenarios using a CHP, the support is

	Unit	Base	PSO zero	NG high	2015	2013
Netincome	m.€	6.31	6.31	9.56	6.72	8.05
- Total cost	m.€	9.67	9.67	18.19	16.82	19.02
- Total income	m.€	15.98	15.98	27.75	23.55	27.07
Support	m.€	11.41	11.41	13.44	13.43	13.44
Input						
Cow slurry, manure	% of input	0.0%	0.0%	0.0%	0.0%	0.0%
Pig slurry, manure	% of input	69.4%	69.4%	69.4%	69.4%	69.4%
Deep litter	% of input	30.6%	30.6%	30.6%	30.6%	30.6%
Output						
Energy converter	Type	CHP (ccgt)	CHP (ccgt)	Methanation	Methanation	Methanation
Capacity of energy converter	MW	9.9	9.9	19.8	20.3	20.4
Energy produced	GWh	116	116	415	414	415

Table 4: Scenario results

97.93€/MWh, and in the scenarios using methanation, the support is 32.41€/MWh, so for less support, more energy is provided. The methanation process, besides getting less support per unit of energy, also pays taxes in the form of electricity tax on the used electricity and excess heat tax.

When biogas producers have chosen to upgrade the later years, it could be explained with an expectation of higher gas prices in the future—an expectation shared with the Danish Energy Agency (Danish Energy Agency, 2012b, 2017). One should be aware that the model chooses the methanation technology, which is not fully commercialised yet.

The NG high scenario gives the highest profit across all of our scenarios by only changing one parameter. We consider this scenario further as a relevant alternative to the Base scenario in the analysis in section 5.

5. A useful profit allocation and the implications

In this section we apply the methods from Bogetoft and Olesen (2007) together with Hougaard (2009), in order to assess three profit allocation mechanisms in relation to viability. We then consider the implications of these allocation methods with regard to the individual choices in the value chain.

Based on the results from the plant level model, we use the base scenario and the NG high scenario for discussing the effects of applying the allocation mechanisms full equality, proportionality and individual rationality. The results from the plant level model makes it possible to write up the alternative profits for each owner in the chain, which is given in table 5.

	Before investments		After investments	
	Description	**Alternative profit**	**Description**	**Alternative profit**
Livestock farmer	Other biogas plant	0 €/ton	Other biogas plant	0 €/ton
Substrate farmer, deep litter	Not delivering substrate	0 €/ton	Leave on field	0 €/ton
Plant	No investment, base	0.07 m.€/y	Sunk cost, base	-1.82 m.€/y
	No investment, NG high	0.07 m.€/y	Sunk cost, base	-1.67 m.€/y
Energy converter, CHP	Heat boiler, base	0.53 m.€/y	Sunk cost CHP plus heat boiler profit	-1.26 m.€/y
Energy converter, Upgrading	No investment, NG high	0.07 m.€/y	Sunk cost	-1.84 m.€/y

Table 5: Alternative profits for the owners in the value chain

5.1. *Results from the profit allocation*

As seen in figure 4, the profit is allocated quite differently depending on the decided profit allocation mechanism. For the proportionality mechanism the allocation would most likely not be considered as equal with the relatively high profits we find in chapter 4.

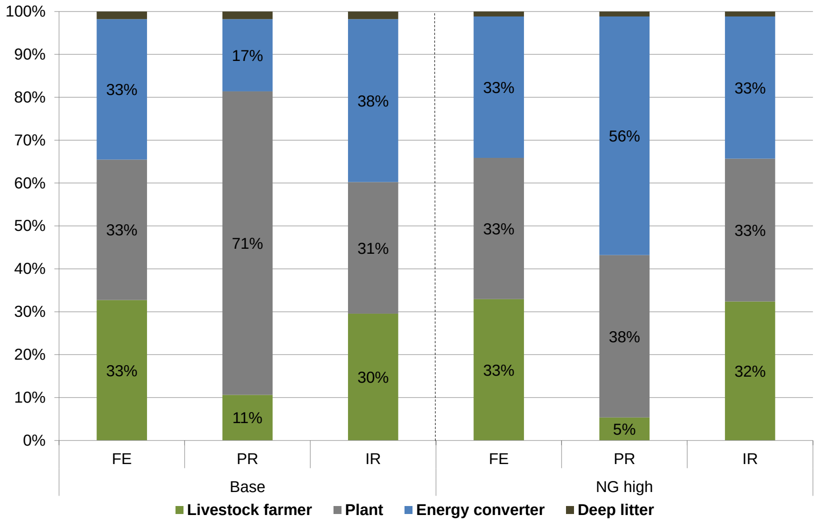

Figure 4: The percentage of the total profit for each owner in all scenarios

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It is obvious that the plant owner would prefer the proportionality distribution, where the highest percentage of the profit can be gained. This is underlined by the exact numbers for the profit for each owner using the allocation mechanisms described in 3.3 that is shown in table 6. We find, that the plant owner would prefer the proportional allocation in both scenarios, while the

		Base			NG high		
	Unit	**FE**	**PR**	**IR**	**FE**	**PR**	**IR**
Netincome	m.€/y	6.31	6.31	6.31	9.56	9.56	9.56
- Livestock farmer	m.€/y	2.06	0.67	1.86	3.15	0.51	3.10
- Deep litter	m.€/y	0.11	0.11	0.11	0.11	0.11	0.11
- Plant	m.€/y	2.06	4.46	1.94	3.15	3.62	3.18
- Energy converter	m.€/y	2.06	1.06	2.40	3.15	5.32	3.17
Price per unit sold							
Manure	€/ton	7.18	3.83	6.70	9.79	3.45	9.66
Deep litter	€/ton	6.75	6.75	6.75	6.75	6.75	6.75
Biogas	€/MWh	63.48	69.29	61.56	78.25	65.68	78.14

Table 6: Results from the allocation using the full equality (FE), proportionality (PR), and individual rationality (IR) mechanisms

livestock farmer would always prefer the full equality. More specifically we find in the base scenario, that the livestock farmer and the energy converter—as opposed to the plant owner—would prefer the full equality or the individual rationality mechanism, which gives them a higher total profit. In the NG high scenario, both the plant and the energy converter would prefer the proportionality mechanism. The change in results from the energy converter's perspective can be explained by the higher costs related to the methanation, which is only reflected in the proportional allocation. The livestock farmer would still prefer the full equality or the individual rationality mechanism.

In the base scenario, the highest biogas price is found using the proportional allocation. This is where the plant would gain the highest profit even though the total profit is lower compared to the NG high scenario. In the NG high scenario, the proportionality mechanism results in the lowest cost of the biogas as the highest profit with this mechanism is given to the energy converter, meaning that less amount of money should be paid to the rest of the chain.

5.2. Risk and adverse selection

Following the notions from Bogetoft and Olesen (2007) and Hougaard (2009) about individual rationality in the profit allocation, we examine whether our profit allocation can be considered to be in the core.

Each owner in the value chain is expected to consider their own gain from participating in the value chain compared to be doing something else. In order to reach a viable value chain it is necessary to find a viable profit allocation, both in order to assure investments and to assure that the most important partners stay in the value chain.

If one owner retracts from the value chain, the profit will be reduced compared to the results in table 4. The new profits obtained is given in table 7 as the percentage of the optimal profit from the base and NG high scenarios, see also section 3.4.

	Before investments		**After investments**	
	Description	**Percentage of profit**	**Description**	**Percentage of profit**
Base				
Livestock farmer	Longer transport distance	97%	Longer transport distance	97%
Substrate farmer	Straw	55%	Straw and sunk cost	51%
Energy converter	Water scrubbing	63%	Water scrubbing and sunk costs	47%
NG high				
Livestock farmer	Longer transport distance	98%	Longer transport distance	98%
Substrate farmer	Straw and sugar beet	75%	Straw, sugar beet and sunk cost	72%
Energy converter	Water scrubbing	56%	Water scrubbing and sunk costs	45%

Table 7: The implications on profit in the biogas value chain when an owner retracts

We find that the importance of the livestock farmer is small as the profit for the entire value chain will only be affected marginally, if 1/3 of the optimal livestock farmers decides to withdraw from the collaboration. This puts the collaboration of farmers in a weak negotiating position, and in particular in a value chain with upgrading, the livestock farmers could risk that the other parties would agree on a proportional allocation principle leaving the livestock farmers with a low profit share, since their costs are also quite low. With a proportional allocation mechanism however, there would be a risk that livestock farmers found this distribution of profits too unequal and unfair, that they would defect and there would be the risk of adverse selection, where farmers would tend to lie costs higher than they are or deliver manure at a lower dry-matter content than promised.

The best alternative to deep litter is to use straw as additional substrate. This would result in a significant lower profit for the value chain, especially if investments have already been made. This votes for finding a good payment to the deep litter farmer even though cheaper alternatives than straw might be possible to find. So 10% of the costs may not be enough.

The relationship between plant and energy converter is more complicated and the risks are high on both sides. In the base scenario where natural gas prices are so low that the preferred solution for the entire value chain would be direct usage in a local CHP, the best alternative (upgrading by water scrubbing) results in a significantly lower profit. Before investments the energy converter does have a fairly good alternative to biogas in the form of a biomass based heat boiler. This could put a pressure on the biogas plant away from the proportional allocation towards full equality or the individual rationality profit allocation. When investments have already been made and if one part decided to withdraw from the collaboration, both parties would loose in the form of sunk costs.

In the NG high scenario, upgrading with methanation is the preferred choice of energy converter and the best alternative is water scrubbing with a profit just above the result from the base scenario. After investments both the plant and the energy converter will have a risk of sunk costs in case the collaboration breaks down, however, while the upgrading plant will have difficulties using the upgrading facility to something else, the plant would probably be able to find alternative options. This leaves the plant in a better negotiating position *before* and in particular *after* investments.

5.3. Discussion of the implications of the results

Danish biogas production have increased remarkably the later years, and among other things there have been two tendencies: that most plants decide to upgrade, and that especially the larger plants have difficulties in finding enough farmers who would commit themselves to deliver the needed manure as input. We argue, that the results presented above can help explaining these tendencies.

5.3.1. Why farmers are hard to involve

The best alternative for the livestock farmers given in table 5, is a common payment of farmers to deliver manure into the biogas plant. They get their manure treated for nothing and in return they are paid nothing (Lemvig Biogas Plant, 2017). This alternative profit is lower than what they could achieve by staying in the value chain with any of the profit allocation mechanisms we have chosen to investigate. Furthermore, the single farmer is often replaceable at low costs cf. table 7. This leaves the farmers in a bad negotiating position and would probably mean that they as a group would accept the proportionality allocation mechanism even if it seem unfair. Instead they may try to be co-owner of the plant in order to achieve more of the profit, and this corresponds well with what we can observe in Denmark, where it is common that farmers are co-owners. So if farmers find it difficult to raise capital to become co-owners, they may not be interested in committing themselves to deliver manure at a low price, simply because they find the profit allocation unfair and therefore not worth any risk.

5.3.2. Why biogas plants would want to upgrade

From the results in Section 4.2, we find that upgrading is the preferred choice when the natural gas price is high. As the prognosis for the natural gas price shows an increase in natural gas prices, it is logical to assume that the new investments in biogas plants have been based on positive projections for the natural gas price implying that upgrading would be the preferred choice (Danish Energy Agency, 2012b, 2017). The "defections" we have seen in real life—when biogas plants have started to upgrade instead of supplying the local CHP (Harder, 2016)—have probably happened when a larger part of the CAPEX is written of, and when contracts should be renewed.

An explanation for *not* choosing CHP could be found in the alternatives for the heat producing energy converter. At first glance, the plant could prefer a CHP as energy converter with a proportional profit allocation, as this could guard the value chain for years with low natural gas-prices, however, this risk may be outweighed by additional profits in years with high natural gas prices, *and* the biogas plant is not guaranteed a proportional distribution.

If a CHP is installed to satisfy a heat demand, the best alternative would often be to install a biomass based heat boiler, resulting in a low heat price in the given area. This alternative gives the CHP a good negotiation power before investments are made, and even though the proportional allocation within the value chain may give a better result than the best alternative with biomass, the alternative could put pressure towards another profit allocation.

After investments are made, both the biogas plant and the CHP would loose, if one of the parties chose to defect and break the chain; however, the actual risk would be lower for the energy converter as he would probably be able to pass on most of the additional cost to the heat consumers. Furthermore, the energy monopoly regulator, DERA (Danish Energy Regulatory Authority) may force the energy converter to pay less for the biogas, for example by demanding an individual rationality profit allocation, and thereby reducing the opportunities for profit for the biogas plant (Danish Energy Regulatory Authority, 1999).

For an investor, an upgrading plant could be a very profitable investment, in particular if a 4% discount rate is the best alternative. From the perspective of the biogas plant an upgrading facility could add good profits to the biogas plant with the right profit allocation. A deviation from the value chain after investments would result in significant costs for the upgrading facility owner, as it would be difficult to use the capacity for something else, so investment costs would be sunk. The biogas plant on the other hand, would also have a risk of sunk cost, but would have a better chance of finding a good alternative usage of the capacity. For example for heat and power production or another upgrading plant. This puts the biogas plant in a much better negotiating position before and after investments, compared to the negotiations with a local CHP. Furthermore, it may be more likely that they can agree on a profit allocation principle.

All these arguments talks in favour for upgrading when looking from the perspective of the biogas plant, who is likely to be the initiator of the project.

6. Conclusion

After it became possible to obtain a similar support for upgraded biogas as biogas used directly in a local CHP, there has been a development where both new and old biogas plants have chosen to upgrade the biogas. Furthermore, new biogas plants tend to have a challenge in achieving enough contracts with livestock farmers who will supply the biogas plant with manure. In order to understand these observations we have combined *optimisation of the biogas value chain* with applied *cooperative game theory* with regards to *profit allocation theory* where focus is on the fairness criteria *equality* and *individual rationality.*

First, we found the optimal configuration of the biogas value chain using a mixed integer optimisation model with a large variety of design options, both with regards to input and investments. We find that the optimal solution is to build a large biogas plant with a high share of manure and a cheap supplementary input substrate; with the specific geographical position of our model plant the optimal input combination is approximately 70% manure and 30% deep litter. We find that the optimal choice of energy converter is a local CHP when natural gas prices are low, and an upgrading facility using methanation when natural gas prices are high. We also find that electricity prices affect total profit in the value chain, however not the optimal choice of technology—at least not to as large an extent as natural gas prices does.

After the optimal configuration was found, we implemented models for allocating the profit using the full equality, proportionality and an individual rationality mechanism. We have concentrated the analysis on the owners from the value chain, that we consider absolutely necessary to achieve support and thereby a proper profit. These owners are a cooperative of livestock farmers, the biogas plant and an energy converter. Our results indicate, that farmers have a low bargaining power in such a group of owners, as their alternative profits are quite low and a least a group of livestock farmers are replaceable. This could result in a profit allocation mechanism as the proportional allocation form, which the farmer collaborative would probably accept, however with low interest in participation. This could result in adverse selection or defection unless the farmer decided to invest in other parts of the value chain.

If the energy converter in the value chain is a CHP, he would have a strong bargaining power before investments are made due to the good alternative of a biomass based heat boiler. It is therefore likely that he could force a profit allocation on the value chain similar to the individual rationality allocation mechanism, where the biogas price is significantly lower than with a proportional allocation. After investments, the bargaining power between the biogas plant and the CHP is more equally distributed, since both would suffer from high losses with new investments. However, the CHP could be supported by the national monopoly regulator (DERA) to force the biogas price down; which has happened several times in the past.

When the energy converter on the other hand is an upgrading facility, the bargaining powers of the biogas plant owner and the upgrading facility owner becomes similar before the investments.

After investments, can the biogas plant owner be considered to be in a better situation since she eventually can choose an alternative energy converter, while alternative applications are hard to find for the upgrading facility, unless the facility is mobile. Furthermore, it is likely that they can agree on a profit allocation mechanism, since all three allocation mechanisms we have investigated result in fairly high profit shares for both the biogas plant and the upgrading plant.

All in all, we find several arguments from theory and our modelling, that supports the observations found with regards to the choices made by Danish biogas value chains within recent years.

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Appendix A. Regulation

Appendix A.1. Regulation related to inputs

The primary input for biogas production must be waste in order to achieve support for biogas in Denmark. Waste can be waste water, manure, or e.g. other agricultural waste products such as waste products from dairy production or from slaughterhouses. While some of these waste products give a high biogas yield, other inputs such as manure will only give a low yield, and as some waste products are limited biogas plants have experimented with energy crops in a mix of manure. However, in order to keep a sustainable biogas production authorities have set restrictions on the level of energy crops (e.g. maize and sugar beet) which can be added in the biogas production. By 2018 this limit will be on a maximum of 12% energy crops that can be added (Danish Energy Agency, 2012a).

Agricultural output is dependent on the amount of nutrients in the soil, and in conventional farming it is common to add a proper amount of fertilizers to the soil. These fertilizers would typically be a combination of manure and mineral fertilizers, however not all the added nutrients are used by the crops and are instead washed out into the ground water. In 1985, with the first Danish waste water action plan, it was decided to set restrictions on the amount of manure and mineral fertilizers that could be used on Danish soils (Environmental Protection Agency, 1985).

A property of digestate (de-gasified manure) is, that nutrients become more usable for the crops, which decreases the need for extra mineral fertilisers in order to achieve the same yield. With the current regulation farmers have been allowed to fertilise the soil in the same way with digestate as with untreated manure. This means that the crops are more fertilised with digestate than with untreated manure. Besides a potential profit from the biogas plant, the primary gain for a participating livestock farmer is an improved fertilizer.

Appendix A.2. Regulation related to output

Biogas support is given to the energy producer from the value chain. Until 2012, the Danish regulation followed some of the same principles as used elsewhere in Europe, where support was given to the produced electricity (EuroObserv'ER, 2014; Lantz et al., 2007; Brudermann et al., 2015). Since the Energy reform in 2012 (Danish Government, 2012), regulation have changed so that biogas upgraded to biomethane and sold on the gas market (through the gas grid) is put on the same regulatory footing as biogas used locally for heat and power production.

The support tariffs for 2016 can be seen in table A.1. The support will last until 2023, however, a part of the support will be phased out from 2016 to 2020 and another part of the support depends negatively on the natural gas price, and thereby reduce the risk of price variations for natural gas.

Appendix A.3. Regulation for methanation

As methanation is a new technology, it has not been implemented in the current support scheme, but following the fundamental principles of the support structure where energy is supported and

Regulation type and description	value
Feed-in tariff on electricity based on Biogas	164.9 Euro/MWh
Feed-in premium for heat-only based on Biogas	55.8 Euro/MWh
Feed-in premium for Biomethane from biogas	59.2 Euro/MWh
Fuel tax on biogas for heat	0 Euro/MWh
Fuel tax on natural gas for heat	34.3 Euro/MWh

Table A.1: Support and tax for upgrading and biogas-based CHP, in 2016-prices

not energy conversion (according to personal communication with Bodil Harder, Danish Energy Agency), we assume that the extra biomethane gained from electrolysis will not gain any support. The support and taxes for methanation are shown in table A.2.

Regulation type and description	value
Feed-in premium for Biomethane from biogas	59.2 Euro/MWh
Feed-in premium for Biomethane from electrolysis	0 Euro/MWh
Fuel tax on electricity for heat based on electrolysis	22.9 Euro/MWh
Tax and transport tariffs on electricity for electrolysis	42.8 Euro/MWh

Table A.2: Support and taxes for methanation, in 2016-prices

Electricity is taxed even more than fossil fuels when electricity is used by private households and for heat production. This also counts for surplus heat. The tax is considerably lower, when electricity is used for industrial production, however any surplus heat from this production used for heating will then be taxed heavily afterwards, this in effect means, that a potential income from the heat generated through electrolysis is close to zero, when the tax is deducted.

A part of the electricity tax is the PSO (public service obligation), which basically is a way to make electricity consumers pay for the development of renewable electricity. The PSO fee is high and even though it is reduced a bit for large consumers it increases total electricity costs significantly. The PSO is phased out from 2017 to 2022 (The Danish Ministry of Energy, Utilities and Climate, 2016), which will reduce the electricity cost significantly for industrial production such as methanation.

Appendix B. Data

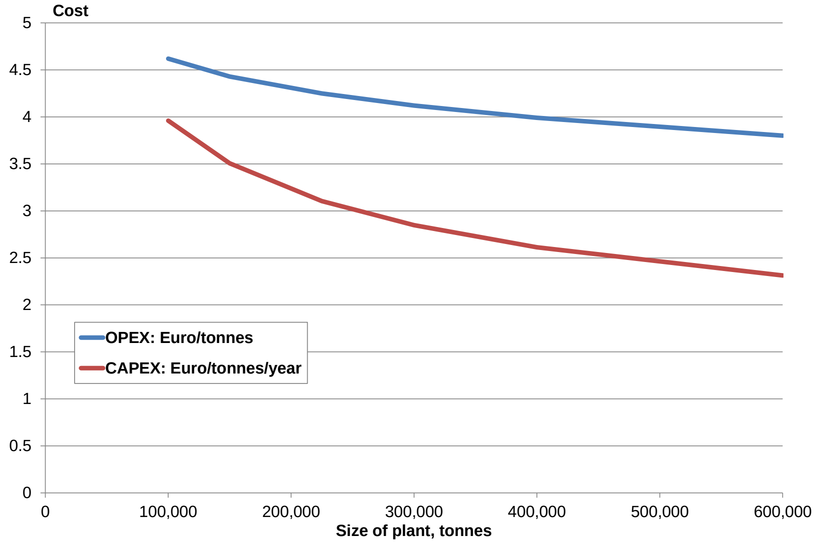

Figure B.1: OPEX and CAPEX for the biogas plant is based on a fitted trendline on the OPEX and CAPEX reported by plants applying for financial support in 2012 in Denmark through the Danish Energy Agency and model plants in the same time. To linearise it, we have used the same break points as in (Jensen et al., 2017).

Cow slurry, manure					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	0.12	0	0	1	4
storage 2	0.12	0	0	1	4
Pig slurry, manure					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	0.12	0	0	1	4
storage 2	0.12	0	0	1	4
Deep litter, substrate					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	0.07	0	0	1	52
storage 2	0.07	0	0	1	52
pretreatment	0.01	0	0.13	1	1
Maize, substrate					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
ensilage	0.00	0	0.78	26	52
storage	0.30	0	0	1	17
Straw, substrate					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	1.72	0	0	1	52
pretreatment	3.61	0	10.19	1	1
storage 2	0.86	0	0	1	52
Sugar beet, substrate					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	0.26	0	1.61	1	16
Washer	0.00	0	2.14	1	1
storage 2	0.26	0	1.61	1	4
cutter	0.00	0	2.14	1	1
ensilage	0.17	0	1.61	26	52
storage 3	0.17	0	1.61	1	4

Table B.3: Data for the case study—input side. OPEX are in €/ton and all CAPEX are annualised with a rate of return of 4% and the given lifetime of the process (20 years are used when no data) and are in €/ton/year. All data are from Abildgaard (2017) except for sugar beet that are from Boldrin et al. (2016).

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Biomass type	Production cost and transport to farm €/ton	Biogas yield Nm^3BG/ton	Dry matter percentage	Extra CAPEX €/ton/year	Extra OPEX €/ton
Cow slurry	0	18	7.5%	0	0
Pig slurry	0	17	5.5%	0	0
Deep litter	0	92	30.0%	1.54	7.51
Maize	30	138	34.0%	0.49	2.41
Straw	27	308	89.0%	4.24	15.42
Sugar beet	26	115	22.0%	0.49	2.41

Table B.4: Production costs and biogas yields of the biomass types. The biogas yield, dry matter percentage and production costs, i.e. without any storage costs etc., as well as transportation costs to the farm are given by Abildgaard (2017), where we assume a transportation distance to the farm from the field of 1.5 for maize, sugar beet, and straw. The extra CAPEX and OPEX for the feedstock are from "EA Energianalyse" (2014).

	Cow slurry		Pig slurry		Deep litter		Digestate	
Radius	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{m}^{TRANS,dig}$
10	75489	1.20	138548	1.20	16298	3.44	51320	1.20
20	543450	2.20	279770	2.20	56260	5.39	109521	2.20
30	690273	3.31	767346	3.31	259280	7.56		
40	819144	4.43	1032999	4.43	83638	9.76		
	Maize		Sugar beet		Straw			
Radius	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{i,m}^{TRANS}$		
10	8004	2.55	1771	2.55	45363	6.72		
20	50609	3.44	6539	3.44	94926	8.73		
30	72005	4.43	8741	4.43	126407	10.96		
40	96998	5.44	9949	5.44	173821	13.23		
50	88888	6.46	14241	6.46	186082	15.52		
60	99251	7.47	11504	7.47	152538	17.81		
70	143800	8.49	13085	8.49	172816	20.10		
80	167910	9.52	17224	9.52	280636	22.39		

Table B.5: Data for the case study—transportation. All costs are in €. Further, the handling price of digestate, $c^{HANDLING,dig_{all}}$, is 0.40€/ton. Data for the last radii is kept out for the types where it is not needed due to too large costs etc. The amount of input in each circle are data from Maabjerg Energy Center (2017), and transportation costs for all substrates as well as amount of digestate delivered in each circle is from Abildgaard (2017).

Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
gasstorage	2.16	0	0	1	12
ironadsorption	25.90	162.4	0	1	1
bioscrub	54.74	32.5	0	1	1
biothrick	44.81	8.1	0	1	1
waterscrub	110.37	30	0	1	1
orgphysscrub	125.09	34	0	1	1
pressswingabsorp	110.37	75	0	1	1
chemscrub	110.37	45	0	1	1
methanation	1471.64	430	0	1	1
boiler	3840.72	2000	1.1	1	1
scgt	38407.18	20000	4.5	1	1
ccgt	57610.77	30000	4.5	1	1
gasengine	64011.96	10000	8	1	1
7to40	52.61	20	0	1	1
1to40	105.22	40	0	1	1
heatstorage	11.92	1.13	0	1	12
Nm3ToMWh	0.00	0	0	0	0
flaring	8093.99	0	0	0	0

Table B.6: Data for the case study—output side (Danish Energy Agency, 2012c; Evald et al., 2013; Pizarro, 2014). All costs are in €, and all CAPEX and fixed OPEX are annualized with a rate of return of 4% and the given lifetime of the process (20 years are used in case of no data). For Boiler, Single-cycle gas turbine (SCGT), Combined-cycle gas turbine (CCGT), and Gas engine CAPEX and OPEXfix are in €/MW/year and OPEX in €/MWh. For the other technologies, CAPEX and OPEXfix are in €/Nm3/h/year and none of these has any assigned variable OPEX. We have used a higher heating value of methane of 39.8 MJ/Nm3 and a lower heating value of 35.9 MJ/Nm3 and assume the methane content of biogas to be 65%, while the methane content of biomethane differs depending on the upgrading technology used.

PAPER E

THE IMPACT OF CO2-COSTS ON BIOGAS USAGE

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The impact of CO_2-costs on biogas usage

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ABSTRACT

The Danish government has set a target of being fossil fuel independent by 2050 implying that a high degree of inflexible renewable energy will be included in the energy system; biogas can add flexibility and potentially has a negative CO_2-emission. In this paper, we investigate the socio-economic system costs of reaching a Danish biogas target of 3.8 PJ in the energy system, and how CO_2-costs affect the system costs and biogas usage.

We perform our analysis using the energy systems model, Balmorel, and expand the model with a common target for raw biogas and upgraded biogas (biomethane). Raw biogas can be used directly in heat and power production, while biomethane has the same properties as natural gas. Balmorel is altered such that natural gas and biomethane can be used in the same technologies.

Several CO_2-cost estimates are investigated; hereunder a high estimate for the expected CO_2-externality costs. We find that system costs increase with CO_2-costs in most cases, while the biogas target becomes socio-economically cheaper. In the case of a very high CO_2-cost, system costs decrease and biomethane becomes the primary fuel. Furthermore, biomethane functions as regulating power and the Danish fuel consumption increases due to a higher electricity export.

1. Introduction

The Danish climate strategy is shaped around a goal of being independent of fossil fuels in all energy consuming sectors by 2050, and one tool among many is biogas. First focus point have been the heat and power sector (from now on called the energy system) in which there has already been a large development in energy savings and implementation of renewable energy. Therefore, an energy system independent of fossil fuels by 2035 has been determined as a stepping stone towards the 2050 goal [1].

Biogas production have been developed in Denmark since the late 1970's with varying focus points [2]. Biogas is a renewable fuel that can be produced from a large variety of inputs such as manure, waste water and other wet substrates, which are expensive to use in other technologies. In Denmark, biogas is primarily based on manure of which there is an abundant supply from the large Danish agricultural industry. The degassed manure from the biogas process has an improved fertiliser value and can potentially improve the water environment as less nutrients are washed out from the fields. Furthermore emissions from the far more potent greenhouse gasses: methane (CH_4) and laughing gas (N_2O) are converted into CO_2-emissions—making biogas one of the few fuels that potentially can reduce greenhouse gas emission effects.

In Denmark, biogas has primarily been used in local, combined heat and power plants (CHPs). As biogas is produced constantly all over the year and it is expensive to store, it is also *used* constantly, i.e. producing a constant stream of heat and power. With an increase in volatile renewable power production, this is not necessarily the optimal usage of biogas. In 2014 new regulation was ratified, such that biogas is now also subsidised when it is upgraded to natural gas quality (biomethane). Biomethane can be transported in the natural gas grid, which allows it to be used *where* it is needed, *when* it is needed.

Biogas has been applied in other analyses on systems optimisation—in particular on the issue of waste as a fuel [3–5]. Biogas is often one fuel out of many and seldom turn out to be the preferred fuel as seen in e.g. Ref. [3] and the national biomass value chain model [6]. In our analysis, we turn our attention to biogas (hereunder biomethane) by including a separate target of biogas usage.

There is a variety of literature on energy systems optimisation using different optimisation models, e.g. Balmorel [7–9], MARKAL/TIMES [10–12], and EnergyPLAN [13–15]. An overview of existing energy systems models can be found in Ref. [16]. With the choice of

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model, it becomes necessary to assess whether the model can include varying properties of the two types of biogas and the target of biogas usage.

In this paper, we consider the year 2025 for which the Danish Energy Agency (DEA) has a prognosis of the biogas production [17], which seems to be aligned with the goal of being fossil fuel independent by 2035. We model biomethane as a substitute fuel for natural gas in an energy systems optimisation model and include a common goal on the use of biogas in the energy system. We allow the model to use biomethane as well as raw biogas and thereby we can compare the two options for the energy system. To our knowledge no other articles have included both raw biogas and biomethane in an energy systems optimisation model to evaluate their usage. The optimisation model is minimising the socio-economic cost of the energy system. From the model, the use of raw biogas and biomethane can be evaluated to find the socio-economic cost of a biogas target in the energy system both as a system cost and a marginal cost of the target. Furthermore, scenarios for different settings of the CO_2-cost is introduced to evaluate the effect on the system cost and the marginal cost of the target.

2. Biogas in Denmark

Biogas production has been developed in Denmark since the late 1970s [2], primarily based on manure and co-substrates from a large agricultural industry; and due to regulation biogas plants have primarily supplied heat and power locally.

As Denmark moves towards being fossil independent by 2050, it becomes necessary to find replacements for particularly coal and natural gas in the energy system. There is already by 2017 a massive development in Denmark where coal to a large extent has been replaced by biomass and wind power. However, the lack of flexibility and predictability among renewable energy sources such as wind and solar power [18] has become a repeated concern, when renewable energy is integrated into the energy system. One suggested benefit from biogas is the potential to add this needed flexibility. The traditionally, Danish biogas usage where biogas is sent directly through a dedicated pipeline to a nearby CHP-plant, can however not be expected to add much flexibility—in some cases it might even work against flexibility, since an effective production of raw biogas only can vary a little and due to high costs with local storing [19] it has to be used gradually while it is produced.

Raw biogas can also be upgraded to natural gas quality and sent as biomethane into the national gas grid. Raw biogas is made of approximately 65% methane and 35% CO_2, and the upgrading process consists essentially in removing this CO_2-surplus, converting the raw biogas into biomethane (98% methane and 2% CO_2). Alternatively, hydrogen from electrolysis could be added to raw biogas, converting the CO_2-surplus into additional methane [20]. This process would increase the biomethane production with roughly 70%. The biomethane can be transported in the gas grid, stored and used with the same flexibility as natural gas in the heat and power sector, in industry or in heavy transport.

2.1. Biogas targets

There is no particular target for Danish biogas usage in 2025. However, a target of using 50% of all manure for biogas production by 2020 was set in the Green Growth Agreement [21]. This is an extensive increase in the biogas production, as currently only 7–10% of the Danish manure is used for biogas production. If 50% of the manure were to be used for biogas production it would correspond to approximately 11 PJ.

The energy consumption prognosis from the Danish Energy Agency (DEA) [17], predicts a 7 PJ increase in total biogas consumption from 10 PJ in 2015 to 17 PJ in 2025. In Fig. 1 the latest and expected development in biogas consumption are depicted (left y-axis) and for comparison the natural gas consumption is also depicted (right y-axis). From this it is clear, that even with a high percentage increase in biogas consumption, it will still be far from the current natural gas consumption.

The latest calculations on future biogas potentials for Denmark corresponds to approximately 60–85 PJ [22,23]. But even with such high production it only corresponds to roughly 10% of the current total energy demand in Denmark, which is around 750 PJ. Furthermore, biogas is considered relatively expensive compared to other renewable technologies. The expected Danish energy consumption is depicted in Fig. 2 together with the energy consumption for the energy system for 2015 and a prognosis for 2025 from the Danish Energy Agency (DEA).

From the 2025 prognosis it becomes clear that an increased biogas production is not expected to be used in the heat and power sector. An increase in biogas consumption is most likely to happen in the transport and industrial sectors according to the Danish biogas task force analysis [24].

2.2. Regulation

As already mentioned, support for biogas was until recently only given indirectly to electricity produced on raw biogas in a local CHP. With the new regulation support is also given to upgraded biogas. The support for 2015 can be seen in Table 1 together with an approximation for the support in 2025. Since the support is dependent on both the natural gas price and the net price index, it is uncertain what the exact support will be in 2025.

With the current regulation, the support for raw and upgraded biogas is in many ways similar and since costs for upgrading are high, a private economic analysis could point to direct use as the preferred usage. According to [25], this is also the preferred choice as long as the plant is small. Following the inflexible production of biogas and the support design, when raw biogas is used in a local CHP, CHP is incentivised to produce constantly, independently of the electricity market. Support for biomethane is given before the biomethane is used and—except for a reduced CO_2-cost—biomethane is expected to have the same properties as natural gas and is taxed the same way. Therefore, the private economic competitiveness of biomethane can already be determined at the gate into the gas system: if the fuel costs including CO_2-costs are sufficiently low, biomethane could compete with natural gas, which may favour upgrading [26,27].

In conclusion, it is reasonable to expect that biogas will be used both raw and upgraded in the future energy system depending on the local conditions, e.g. the local district heating demand.

3. Biogas in the energy system

Based on the above, we find it reasonable to include both raw biogas and biomethane when we model biogas within a Danish energy system context. The raw biogas and biomethane should be included in the energy systems model with different properties, e.g. cost and efficiency, and the common target should be handled by the model.

3.1. Balmorel

We choose to use the energy system model, Balmorel [28], for analysing the use of raw biogas and biomethane. Balmorel is a bottom-up model in which the energy system can be optimised

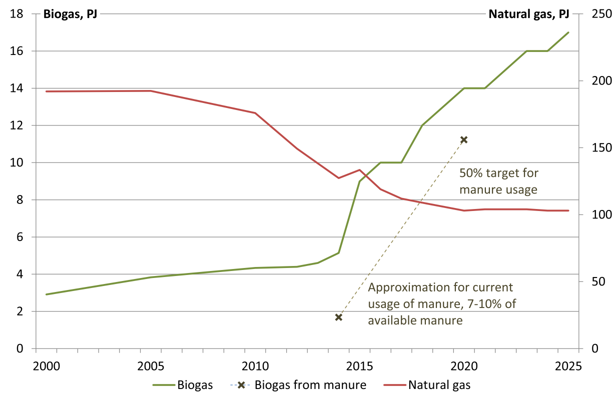

Fig. 1. Biogas target shown on the left y-axis compared to the natural gas demand on the right y-axis.

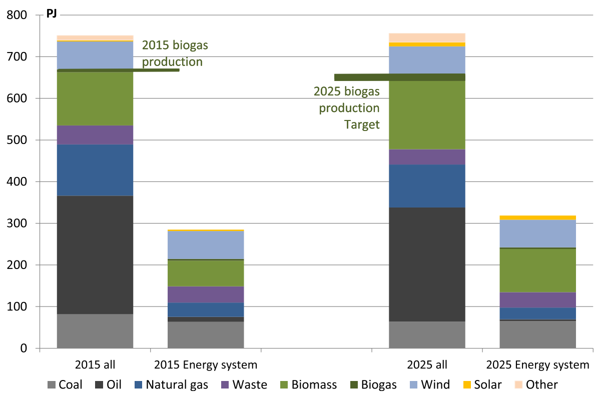

Fig. 2. Danish fuel consumption.

Table 1
Direct and indirect support for biogas, in 2015-prices.

Regulation type	2015	2025
Electricity feed-in tariff, CHP - raw biogas	16.8 Eurocent/kWh	12.8 Eurocent/kWh
Avoided fuel tax on heat, CHP - raw biogas	3.1 Eurocent/kWh	3.1 Eurocent/kWh
Biogas feed-in premium, biomethane	16.8 Euro/GJ	12.8 Euro/GJ

using an economic dispatch model, i.e. assuming all energy generating units are always online. The general economic dispatch model for electricity generation without investments can be written as:

$$\text{Min. } z = \sum_{t \in \mathscr{T}} \sum_{a \in \mathscr{A}} \sum_{g \in \mathscr{G}} \sum_{s \in \mathscr{S}} cost_g vge_{a,g,s,t} \tag{1}$$

$$\text{S.t. } vge_g^{min} \leq vge_{a,g,s,t} \leq vge_g^{max} \quad \forall a \in \mathscr{A}, g \in \mathscr{G}, s \in \mathscr{S}, t \in \mathscr{T} \tag{2}$$

$$\sum_{g \in \mathscr{G}} vge_{a,g,s,t} = d_{a,s,t} \quad \forall a \in \mathscr{A}, s \in \mathscr{S}, t \in \mathscr{T} \tag{3}$$

$$vge_{a,g,s,t} \geq 0 \quad \forall a \in \mathscr{A}, g \in \mathscr{G}, s \in \mathscr{S}, t \in \mathscr{T} \tag{4}$$

Line 1 is the total cost of producing on the installed technology type g. Here $cost_g$ is the cost of producing one unit of power on technology g and $vge_{a,g,s,t}$ is the amount of electricity produced on technology g in area a in all time periods given by season s and time t. Equation (2) ensures that each technology produces within its limits given by a minimum production limit, vge_g^{min}, and a maximum production limit, vge_g^{max}, in all areas and time periods. Equation (3) ensures that the electricity demand is met in all areas and time periods. Equation (4) ensures that the production is non-negative for all technologies in each area at all time periods. All used nomenclature can be seen in Appendix A. The economic dispatch problem can be extended to include heat-only technologies as well as combined heat and power technologies. This extension is not covered here, however, Balmorel includes both power and heat generation, as well as transmission within countries and between countries. The reader can refer to [28] for more details on modelling in Balmorel.

Balmorel is adoptable to any choice of geography, however it is used mostly in the Nordic and Baltic countries. Balmorel can be extended using several different add-ons, e.g. a unit commitment add-on, a policy add-on, and a time aggregation add-on. In this paper we use the economic dispatch model with optimisation of investments, and the combination technology add-on (Combtech) described in Section 3.3.

Balmorel performs an economic optimisation with a simplistic representation of a socio-economic analysis, which do not include all externalities. The socio-economic optimisation is a cost-based analysis, using neither national taxes nor subsidies, and costs used in the model are expected market prices.

3.2. Modelling of biogas in the energy system: limitations and delimitations

Balmorel is run using economic dispatch, meaning that the fuel with the lowest cost for the system is used first and the most expensive fuels are used as regulating power. Given the inflexibilities of biogas production and expensive local storage [19], raw biogas cannot be used as regulating power in the system. This could be included in the model by forcing the model to use the raw biogas constantly. This addition would make the model an integer programming model and would increase running time significantly. With a long running time already before this addition, it is not considered a viable solution and the model is kept linear. Alternatively, the model could be forced to flare a certain percentage of the raw biogas. This, however, would require that the raw biogas is used as base load and, as described in Section 6.2, the main investments for biogas are made in regulating power technologies. We therefore address this issue manually in the result analysis; and to avoid an extensive usage of raw biogas as regulating power—giving raw biogas an incorrect competitive advantage compared to biomethane—we do not allow the model to invest in new plants using raw biogas as fuel.

Aggregation is widely applied in Balmorel to make the model both faster and—as in the case of fuel usage—more specific. Time aggregation is applied by using a number of weeks during the year with a number of hours per weeks specified by the user. These choices will make the model faster than running the full year and—with a clever choice of weeks over the year—the results will be close to the full year model.

Fuel usage aggregation means that each technology has a specific fuel assigned to it with specific properties, hereunder efficiencies. One plant in the real world with different fuel inputs, would therefore be displayed in Balmorel as a number of technologies corresponding to the number of fuel inputs. Balmorel then optimises the fuel usage considering fuel costs, technology properties, capacity availability and so forth. At the same time, many plants in a given area are aggregated into one representative plant, meaning that in each area in Balmorel there can only be one plant of each technology.

A combined heat and power plant (CHP) using raw biogas cannot easily substitute the biogas with another fuel. A CHP using natural gas can however substitute the natural gas with biomethane, as this is essentially the same.

3.3. Combtech: combination of two technologies

The relevant add-on for combining two technologies is called Combtech. To our knowledge, Combtech has only been used in one paper [5], where it is used to evaluate how waste should be used in the energy system. Combtech can combine two technologies, a primary technology and a secondary technology, with similar characteristics, e.g. efficiencies, lifetime, and fuel type. In our case, the only characteristic biomethane and natural gas technologies do not share is the fuel type, which results in different CO_2-emissions and fuel costs.

To allow substitution of fuels in a specific plant, the following constraints must be revised in Balmorel:

- Capacity constraints for existing and new energy conversion capacities
- Loss of electricity generation per unit of heat generated on extraction units for existing and new capacities

The capacity constraint is defined for existing electricity units, existing heat units, new electricity units, and new heat units. For the sake of simplicity, this constraint is only given for the existing electricity units but can easily be transferred to the other types by a name change in variables and sets. The existing electricity units g are in the set $\mathscr{G}^{elec,1}$ and $\mathscr{G}^{elec,2}$, where the first set is for the primary technologies and the second for secondary technologies. $vge_{a,g,s,t}$ is the production of electricity in area a, on technology g, season s and time t. The primary and secondary technologies are given from g by $\mathscr{G}^1(g)$ and $\mathscr{G}^2(g)$, respectively. The capacity of technology g in area a is given by $c_{a,g}$ and the combination of areas and technologies where capacity exists is given by the set $\mathscr{AGK}$. The capacity constraint is:

$$vge_{a,g,s,t} + \sum_{g_2 \in \mathscr{G}^2(g)} vge_{a,g_2,s,t} \leq c_{a,g} \quad \forall a \in \mathscr{A},\ g \in \mathscr{G}^{elec,1}, \\ \{a,g\} \in \mathscr{AGK}, s \in \mathscr{S}, t \in \mathscr{T} \tag{5}$$

Here the generation on the primary technology and all related secondary technologies are added and can not exceed the installed capacity.

An extraction unit can generate both heat and power, but in contrast to a back-pressure unit, the ratio between heat and power is not fixed. Instead the extraction unit will have a loss of electricity produced per unit of heat generated. The loss, which is given by the so-called Cv-line, is defined for both existing units and new units and is given here for the existing units. As for the capacity constraint, the constraint for the new units is similar and can be derived by a name change in variables and sets. The electricity loss of the extraction unit $g \in \mathscr{G}^{ext,1}$, is modelled using the parameter, C_g^v, which is assumed constant. The loss of electricity generation per unit of heat generated by extraction units is given by:

$$vge_{a,g,s,t} + \sum_{g_2 \in \mathscr{G}^2(g)} vge_{a,g_2,s,t} \le c_{a,g} - C^v_g vgh_{a,g,s,t} - \sum_{g_2 \in \mathscr{G}^2(g)} C^v_{g_2} vgh_{a,g_2,s,t}$$
$$\forall a \in \mathscr{A},\ g \in \mathscr{G}^{ext,1},\ \{a,g\} \in \mathscr{AGK}, s \in \mathscr{S}, t \in \mathscr{T} \tag{6}$$

When optimising, Balmorel can then decide whether to use natural gas or biomethane in the production—taking fuel prices and restrictions into consideration.

3.4. Modelling the biogas target

The common biogas target for raw biogas and biomethane is included by a new constraint. The model is based on the abbreviations used above and the following is added. $\mathscr{A}(c)$ is the areas related to country c. $vgf_{a,g,s,t}$ is the used fuel in area a on technology g in season s in time t on installed capacity and $vgfn_{a,g,s,t}$ is the same for new capacity. $fuel(g)$ is the fuel type used on technology g. The parameter called $GMIN2F_{c,f,f'}$ is added to the model with the target described in Section 4 and represents the target for fuel f and f' in the country c. The target should be given in GJ.

The common target can be handled by the following constraint:

$$3.6 \cdot \sum_{a \in \mathscr{A}(c)} \left(\sum_{\substack{g \in \mathscr{G} | \\ fuel(g) = f}} \sum_{s \in \mathscr{S}} \sum_{t \in \mathscr{T}} \left(vgf_{a,g,s,t} + vgfn_{a,g,s,t} \right) + \sum_{\substack{g \in \mathscr{G} | \\ fuel(g) = f'}} \times \sum_{s \in \mathscr{S}} \sum_{t \in \mathscr{T}} \left(vgf_{a,g,s,t} + vgfn_{a,g,s,t} \right) \right)$$
$$\ge GMIN2F_{c,f,f'} \qquad \forall c \in \mathscr{C},\ f \in \mathscr{F},\ f' \in \mathscr{F} \tag{7}$$

The first line represents the amount of fuel type f that is used and the second line represents the amount of fuel type f' used in the model. As the amount of fuel used is given in MWh and the target in GJ, the left hand side is multiplied by 3.6. Only the countries and fuels for which there are a specified target are bound by the constraint.

4. Assumptions and data

For this analysis we simulate the Nordic countries and Northern Germany with a focus on Denmark, i.e. only a Danish target of biogas consumption. The countries are further divided on a regional level corresponding to the regions on Nordpool—except for Northern Germany, which is divided into three regions. The regions are further divided in up to 10 areas based on the demand, size and geography.

We model one year, 2025, using four full weeks, one in each season. Furthermore, we perform a simple socio-economic analysis, i.e. cost prices from a Danish viewpoint together with no taxes nor subsidies. CO_2-emission is the only externality included in the optimisation and is represented by a socio-economic cost of CO_2. Focus is on climate targets, as this is where biogas has a competitive advantage due to a negative CO_2-emission in CO_2-equivalents. This assumed negative emission is based on avoided methane and N_2O -emissions when manure is treated and thereby converted into biogas and digestate instead of being distributed directly on the fields. The CO_2-emission value has been calculated by using the data from Refs. [29,30].

Fuel costs are mainly international market prices, following the assumption that most fuel prices will not be affected significantly by Danish fuel consumption. The primary source for fuel costs is the Danish Energy Agency (DEA) 2016-prognosis for socio-economic analysis, which is estimated on the basis of IEA prices [31]. The natural gas price is for example based on IEA prices adjusted to Danish price levels.

Fuels with high transportation costs, which do not enter the international markets, such as some biomasses, have an estimated cost which follows the closest substitute [31]. In the case of for example straw, the closest substitute is wood chips. Biogas costs are estimated on the basis of production costs found by using a profit optimising plant model with an input combination of manure and straw [27]. The straw price is the same as used in the energy systems analysis. The plant is large, using as input 600.000 t/y and generating a biogas yield of approximately 34 Mm3/y. Costs are found both in relation to raw biogas and when upgrading costs for the biomethane are included. The upgrading to biomethane is done by water scrubbing.

Type of fuel cost method, fuel costs and CO_2-emissions are listed in Table 2. All costs are in €2015 prices.

4.1. The significance of price changes

The Danish Energy Agency (DEA) assumes that fixed fuel prices will increase over the years, however, not extraordinarily [31]. There is a possibility that particularly biomass prices will increase more rapidly than expected, which could change the overall system results significantly. As we use the straw price as input to the biogas production, higher biomass prices will have an effect on the biogas costs and thereby an effect on the biogas target. However, higher biomass costs would improve the competitiveness of biogas compared to biomasses, as straw is a minor part of the biogas costs. The most important factor in relation to price changes is expected to be price changes for the nearest substitute, in this case natural gas.

4.2. Targets and maximum consumption

As mentioned in section 2.1 there are currently no biogas targets, so we set the biogas target following the biogas consumption prognosis for biogas in the heat and power sector from DEA [17], where biogas consumption in the energy system is expected to decline from 4.3 PJ to approximately 3.8 PJ. This assumption follows the conclusions from the Biogas Taskforce as well as the general development in the Danish energy system, where natural gas based combined heat and power production is crowded out by primarily wind power [32]. The used target and limitations can be seen in Table 3.

We do not use a target for natural gas consumption, however we set a limit following the DEA estimated use by 2025. In this estimation, it seems that the goal of a renewable founded heat and power production by 2035 is taken into account. Furthermore,

Table 2
Fuel data.

	Type of price	Price, €/GJ	CO_2-emissions, kg/GJ
Fossil Fuels	Market prices [31]	Predicted avg. prices	Standard figures [31]
Biomasses	Comb. of market and cost prices [31]	Predicted avg. prices	Avg. figures calculated on expected usage [30]
Raw biogas	Cost calculated [27]	10.2	−77 [30]
Biomethane	Cost calculated [27]	12.1	−77 [30]
Natural gas	Market prices	6.7 [31]	56.8 [31]
Straw	Comb. of market and cost prices	6.3 [31]	11 [29]

Table 3
Forecasts and targets [17].

	Actual, Energy system, 2015	Forecasted, Energy System, 2025	Target or Maximum
Biogas	4.3 PJ	3.8 PJ	Target
Natural gas	34.5 PJ	28 PJ	Maximum

there is a fixed usage of waste which is based on calculations using the FRIDA model [33] using the recycling targets from Ref. [34]. Last, an upper bound on wind potential is used, which is based on the IEA report [35].

4.3. Production capacity

We apply the existing generation capacity in the model by 2025, which for the Danish capacities are based on data from the Danish counting of energy production capacity by 2016 [36]. These capacities have been projected up to 2025 following expected remaining lifetimes and efficiencies. We allow the model to invest in further capacity in order to fill the gaps from existing, depreciated capacity and new demand. The given technology costs are found in the technology catalogues from DEA [37] and new investments are depreciated with a 4% interest rate following the instructions for socio-economic analysis in Denmark [38,39]. Furthermore, it is assumed that all investments have a 20 year lifetime.

In Table 4 the existing capacities for technologies using biogas are shown along with their average efficiencies. The model is allowed to invest in new capacity using natural gas/biomethane, but it is not allowed to invest in capacity using raw biogas. This is due to the challenges with raw biogas, where it is difficult to resemble reality and force the model to use the same amount of biogas all over the year, as explained in section 3.3. As it turns out, this will only be an issue in one scenario.

5. Scenarios

In order to understand the socio-economic costs from setting a target for biogas usage in the Danish Energy System, two primary scenarios are considered. A Base-scenario with no biogas target and a Target-scenario, with a target for biogas. A determining factor for the result is the socio-economic cost of CO_2. When the socio-economic cost of CO_2 is high, fossil fuels becomes relatively less competitive. In the case of biogas, this becomes even more relevant,

Table 5
Settings for the scenarios.

Scenario	Target	CO2-cost level	CO2-cost, €/ton
Base	−	Average	15.3
Target	+	Average	15.3
CO2High/Base	−	High	23.1
CO2High/Target	+	High	23.1
CO2Low/Target	+	Low	7.5

as biogas is assumed to have a negative CO_2-emission. Therefore three secondary scenarios are added investigating the importance of the CO_2-cost. The settings used can be seen in Table 5. In Fig. 3, the CO_2-cost is added to the fuel cost to illustrate the significance of the CO_2-cost. It becomes clear that the closest substitute to biogas, natural gas, continue to be cheaper than biogas—even in the high CO_2-cost scenario, given the expected development in natural gas prices.

The actual socio-economic cost of CO_2-emissions from the Danish energy production is difficult to estimate correctly. Therefore, we followed the recommendation from DEA [31] to use different prognoses for the CO_2-quota price, assuming, that this to some extent corresponds to the socio-economic cost. We used the DEA 2015-prognosis for the high and low CO_2-quota price which is based on current CO_2-quota prices and the IEA World Economic outlook prognosis from 2015. Finally, we used the average of the two scenarios. All scenarios are shown in Table 5.

5.1. CO_2-externality cost scenarios

The European CO_2-quota prices are based on the expected marginal costs of CO_2-emission reduction given the political decided cap on CO_2-emissions within the CO_2-quota affected sectors. As the cap is politically decided it is not necessarily related to any expectations for the actual CO_2-externality costs, and compared to the literature, these costs also seem rather low. In Ref. [40] several estimations for the CO_2-externality costs from the

Table 4
Technology data [36,37].

	Existing capacity		Efficiency	
	Raw biogas	Combination technology	Raw biogas	Combination technology
Heat Only	19 MW	3161 MW	80.7%	95.6%
CHP	107 MW	934 MW	89.9%	90.5%
Electricity Only	0.3 MW	0.8 MW	31.7%	44.0%

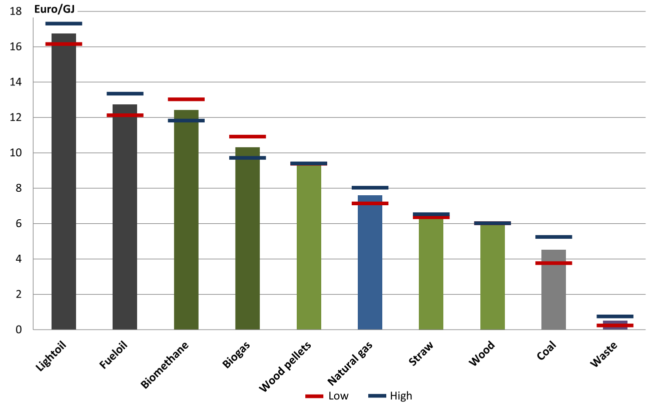

Fig. 3. Fuel costs, when the CO_2-cost is added; for average, low, and high CO_2-costs.

literature are collected and evaluated, and from this a lower bound for the social cost of CO_2 is formed. This bound is high compared to other cost estimates in the literature [40].

To see what happens to the biogas consumption when a higher CO_2-cost is used in the model, we include this lower bound as the Van den Bergh CO_2-cost in the CO2Bergh/Target scenario. Further, we use the lower estimate from Ref. [41] in the CO2Dice/Target scenario to compare the results from the DEA estimates on marginal CO_2-emission reduction costs to the estimated CO_2-externality costs from Refs. [40] and [41]. The used CO_2-costs and the resulting fuel costs for natural gas, biomethane, and biogas can be seen in Table 6 for the scenarios with high CO_2-cost.

It is noticeable that the Dice CO_2-externality costs are quite close to the estimated high CO_2-quota price from the DEA.

6. Results

Seven scenarios have been run: two primary and three secondary, as well as two sensitivity analysis scenarios of the CO_2-costs.

6.1. System cost

Five parameters are presented in Table 7 giving the overall results from the scenario runs. The objective function value, OBJ, constitute the total system costs of the given scenario in Million Euro. Whereas Δ OBJ shows the additional system cost of a scenario in relation to the base scenario. The system cost increases when a biogas target is added, as the model would otherwise have used the biogas already. However, the results show, that the system cost increase is low, compared to a high CO_2-cost. This makes sense as biogas corresponds to approximately 1.6% of the fuel usage in the target scenario while fossil fuel usage corresponds to approximately 36% of the fuel usage in all scenarios. Furthermore, we find that it becomes relatively less costly to add a biogas target as the CO_2-cost increases, which is due to the negative CO_2-emissions from biogas.

The marginal cost of forcing a biogas target of 3.8 PJ on the system is between 1.23 and 3.36€/GJ depending on the CO_2-cost. In order to make biogas socio-economically worthwhile, the actual CO_2-externality cost should prove to be even higher in order to call the biogas target socio-economic beneficial. Alternatively, other benefits from biogas production could be considered, such as positive externalities from e.g. reduced smell, increased quality of agricultural fertilisers, possible reduced nutrient releases to groundwater, or job creation in rural areas.

The last parameters, CO_2-total and CO_2-DK, show the amount of CO_2-emissions for the scenarios. Here it shows that a biogas target changes the CO_2-emissions in Denmark more than the high CO_2-cost. The Danish biogas target has an effect on the total CO_2-emission. This can be seen by the total CO_2-emission in the target scenarios being reduced more than the Danish CO_2-emissions and can be explained by an increase of electricity transmission to Germany, which reduces the use of coal in Germany and therefore a decrease in the CO_2-emissions.

6.2. Fuel and capacity usage

In Table 8 it shows that the upper bound on natural gas usage is binding through all the scenarios. In all scenarios, however, only approximately 11–12% of the installed capacity is used, and only a small fraction of the used capacity is using biomethane. An explanation of this low usage combined with new investments could be that gas primarily is used for regulating power. This is substantiated by 80–98% of the new investments in combination technologies are in power producing capacity. Both raw biogas and biomethane are used in the target-scenarios, however, raw biogas is preferred to biomethane due to the lower fuel costs. The model does not distinguish between raw biogas and combination technologies as

Table 6
CO_2-costs for the high CO_2-cost scenarios, €2015/ton.

Scenario	CO2-cost	Natural gas	Biomethane	Biogas
CO2High/Target	23.1	8.0	11.8	9.7
CO2Dice/Target	30.3	8.4	11.3	9.2
CO2Bergh/Target	99.2	12.4	6.0	3.8

Table 7
Results of the five scenarios. OBJ is the objective function value, ΔOBJ is the change in the objective function from the Base scenario, MTE is the marginal value of the biogas target constraint (7), and CO_2-total and CO_2-DK are the CO_2-emissions from the total energy system and for the Danish energy system.

	Base	Target	CO2High/Base	CO2High/Target	CO2Low/Target
OBJ, M€	35,798	35,804	37,928	37,931	33,385
ΔOBJ, M€	–	6	2,130	2,133	−2,414
MTE, €/GJ	–	2.22	–	1.23	3.36
CO_2-total, MT	296.7	296.3	253.1	252.7	320.7
CO_2-DK, MT	8.0	7.8	8.1	7.8	7.8

Table 8
Fuel usage, basic results. BM-COMB represents the percentage usage of biomethane in the combination technologies and %-COMB represents the percentage that the combination technologies are used.

	Base	Target	CO2High/Base	CO2High/Target	CO2Low/Target
Biogas usage, GJ	485,731	2,083,290	776,758	2,517,432	1,964,166
Biomethane usage, GJ	–	1,716,710	–	1,282,568	1,835,834
Natural gas usage, GJ	28,000,000	28,000,000	28,000,000	28,000,000	28,000,000
BM-COMB	0%	5.8%	0%	4.5%	6.1%
%-COMB	11.7%	12.1%	11.0%	11.3%	11.8%
New COMB-capacity, MW	525	568	352	389	735

we have not included the problems with flexible usage of raw biogas in the model, see section 3.2. These observations emphasise the need of not allowing the model to invest in new capacity using raw biogas.

Fig. 4 displays the normalised fuel usage in the base and target scenarios in order to compare how fuel consumption differs. As the biogas target represent a small share of the total energy consumption it is no surprise, that the overall fuel consumption is quite similar. However, it can be seen that the additional biogas usage is substituting use of oil and heat pumps, but also biomass.

Fig. 5 presents the three target scenarios and displays the significance of the CO_2-costs on fuel usage. The figure shows, that the usage of coal, natural gas, waste, wind, and sun does not change through the scenarios. Relating this to Fig. 3, an explaining factor can be that neither coal, natural gas nor waste changes position in the ranking of fuel costs with these changes in the CO_2-costs. When the CO_2-cost is low, it is preferred to use heat pumps, oil, and surplus heat in the system, whereas biomass and biogas is preferred when the CO_2-cost is high.

For the CO2Low/Target scenario, the usage of biomethane is

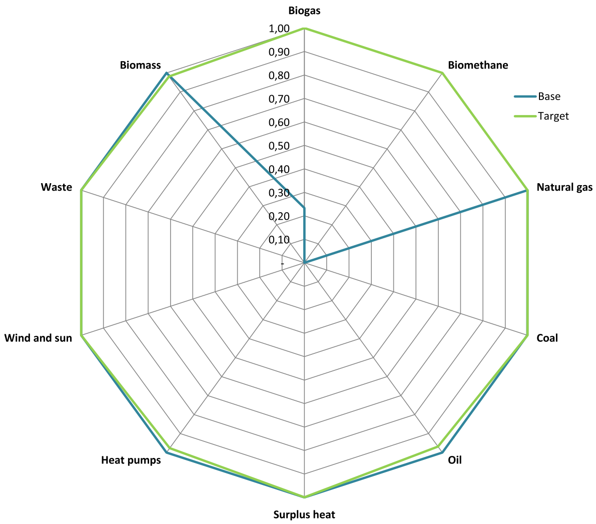

Fig. 4. Normalised fuel usage for Denmark in the base and target scenario.

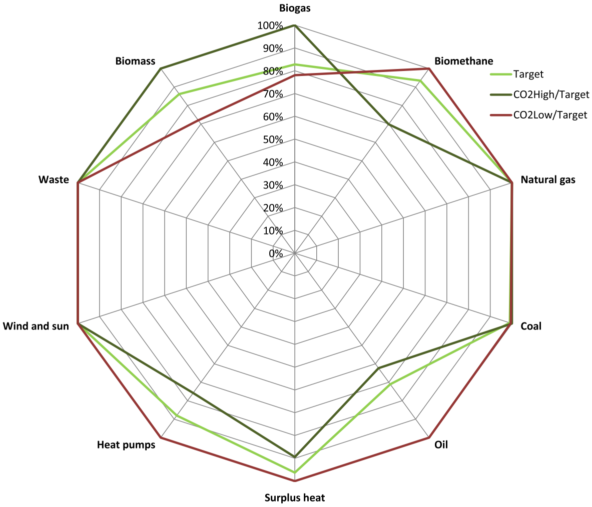

Fig. 5. Normalised fuel usage for Denmark in the target scenarios.

higher than in any other scenario. This is due to the fact that when comparing raw biogas and biomethane, the fuel costs become relatively closer to each other when the CO_2-cost is low compared to when the CO_2-cost is high. Biomethane is still more expensive, but when the costs are relatively closer, other factors become more determining for the result. These factors are e.g. technology efficiency, investment and operational costs, and the relative demand between heat and power.

Waste, wind, and sun are used equally across all scenarios. This is due to the fact that the maximum restrictions on these energy sources are binding in all scenarios. It is out of the scope of this paper to evaluate further on the restrictions. The results, however, indicate that the restrictions have an influence on the final results.

6.3. Usage of raw biogas in the system

Raw biogas is preferred to biomethane in all scenarios due to the lower fuel costs of raw biogas while not all inefficiencies from the real world are implemented in the model, as e.g. the need for an almost constant use of raw biogas. Fig. 6 represents the usage of raw biogas in the CO2High/Target scenario, where the biogas usage in GJ for CHP-units relates to the right y-axis and boilers plus electricity-only units relates to the right y-axis. It is clear, that raw biogas primarily is used in CHP-units and mostly during winter and autumn (first and last period) and as regulating power during spring and summer. If a real world biogas based CHP had this consumption pattern, it would result in approximately 30% of the gas being flared, which would increase the cost of using raw biogas considerably. More likely, the plant would produce constantly, thus decreasing the value of the output for the system and thereby also the value of the raw biogas.

6.4. When the CO_2-externality costs are implemented

While the first scenarios presented in this paper relate to estimated CO_2-cost from a CO_2-quota system, the CO_2-costs in the last two scenarios are related to estimations of the actual CO_2-damage costs: a low and a high estimate. As given in Table 6, the estimated CO_2-costs in the CO2Dice/Target scenario are quite close to CO2High/Target scenario, which is also reflected in the result summary in Table 9. However, the interpretation of the costs is not the same. Total system costs increase slightly from the CO2High/Target to the CO2Dice/Target scenario, while the marginal costs of having a target for biogas usage approaches zero, so it seems that the CO_2-costs approaches a breaking point where the needed biogas would be used without a target.

Total system costs are low in the CO2Bergh/Target scenario compared to the other high CO_2-cost scenarios. This decrease in system costs is based on fuel costs of raw biogas and biomethane, which are low due to their negative CO_2-emission. This also result in a high use of biomethane, which by far exceeds the target and thereby reduces the marginal cost of the biogas target to zero.

In Table 9 we see a small decrease in both usage and installation of combination technologies in the CO2Dice/Target scenario, and in Fig. 7, we see that biomass seems to have become relatively more attractive in the CO2Dice/Target scenario. In the CO2Bergh/Target scenario on the other hand, both the degree of capacity usage and investments increase, which could also be expected considering the increased usage of biomethane—reflected in Fig. 7.

The CO_2-emissions show to be negative for both Denmark and the total energy system for the CO2Bergh/Target scenario as shown in Table 9. The negative CO_2-emission in Denmark is explained by the excessive usage of biomethane in Denmark as shown in Fig. 7. For the total system, the important contributor to negative CO_2-emissions is Germany where biomethane is also used to a large

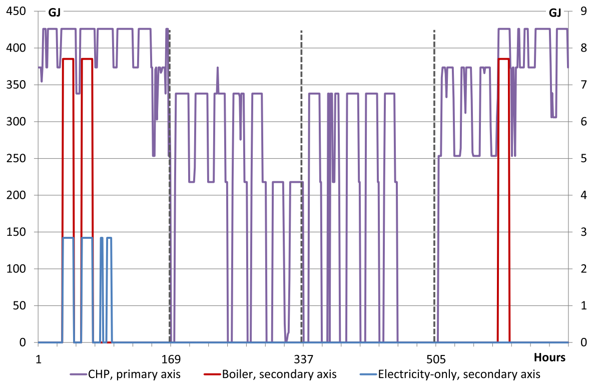

Fig. 6. Usage distribution of raw biogas in the CO_2 High/Target scenario.

Table 9
Results of the high CO_2-scenarios. MTE is the marginal value of the biogas target constraint (7) and %-COMB represents the percentage that the combination technologies are used. The capacity installed on the combination technologies are given by New COMB-capacity, and the CO_2-emissions for the system and for Denmark is given by CO_2-total and CO_2-DK.

	CO2High/Target	CO2Dice/Target	CO2Bergh/Target
OBJ, M€	37,931	39,685	36,437
MTE, €/GJ	1.23	0.13	–
%-COMB	11.3%	10.7%	44.3%
New COMB-capacity, MW	389	352	3443
CO_2-total, MT	252.7	232.4	−178.4
CO_2-DK, MT	7.8	7.7	−13.3

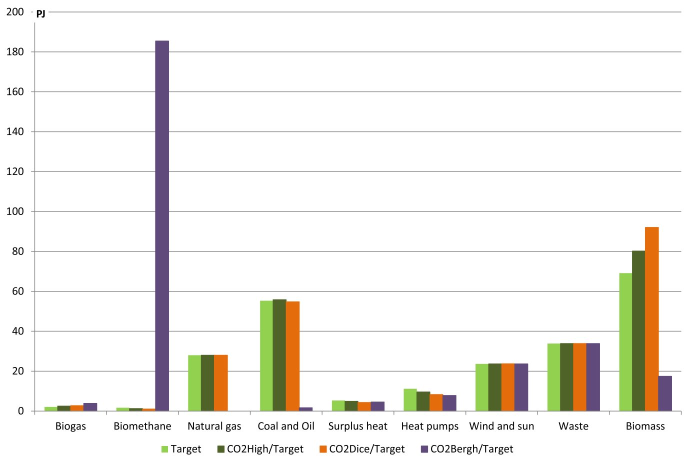

Fig. 7. Fuel usage in Denmark for the scenarios with high CO_2-cost.

extent—resulting in negative CO_2-emissions for the whole system.

The accumulated amount of fuels used in the CO2Bergh/Target scenario exceeds the fuel usage in any of the other scenarios. This can be explained by electricity based on biomethane becoming cheap enough to substitute a large amount of electricity production in Germany, resulting in an increased electricity export and a higher fuel usage in Denmark.

The natural gas consumption in this scenario has been replaced completely with biomethane, which then function as a base load provider during winter and autumn, and provider of regulating power during the summer period. This underlines, that biomethane can indeed function as a fuel for regulating power, using the gas transmission net as energy storage—in a scenario where CO_2-costs are very high.

The suggested biomethane consumption in CO2Bergh/Target scenario exceeds by far the sketched biogas potential in section 2.1, which means that more biogas would have to be produced. This could be through the addition of imported biomasses or e.g. grown algaes, which are not considered in the current prognosis for biogas potentials [22,23]. Furthermore, biogas could be upgraded by methanation where hydrogen is added to the raw biogas, such that excess CO_2 and hydrogen are converted into CH_4 and thereby increase the biomethane production by approximately 70% [42]. The hydrogen could be produced when electricity prices are low. Potentially, this can help even-out the electricity price and give an effective way to store electricity when there is an oversupply. How the additional biomethane is produced and interacts with the energy system is out of scope of this paper. It can, however, be expected that biomethane made by methanation will affect the assumed CO_2-emission related to biomethane such that less CO_2 will be reduced per GJ biomethane produced. When fed into the calculation, this should make the model less eager to use the large amount of biomethane.

7. Conclusion

In this paper we investigated the socio economic system costs of having a biogas target in Denmark, and how CO_2-costs affect the system costs and biogas usage. To do this, we used the energy system model Balmorel with the possibility to combine natural gas with biomethane in one technology. Furthermore, we set a target for raw biogas and biomethane corresponding to the predicted amount used in the heat and power sector in 2025. First, the model was applied using predictions of CO_2-costs from the Danish Energy Association. Then, we added two sensitivity analysis scenarios where we applied higher CO_2-costs corresponding to estimates for the actual CO_2-externality costs found in the literature.

From our analysis, we see that we need a very high CO_2-cost estimate in the area of the CO_2-costs estimated by Van den Bergh [40] before biogas or biomethane is worthwhile using in large amounts. When increasing the CO_2-costs, the biogas target becomes less costly while the total system cost increases. First when CO_2-costs are very high, biogas becomes worthwhile and used to such an extent, that total system costs decline. Even though the very high CO_2-cost might not be justified, there could still be arguments for forcing the system to use biogas, as there are other positive externalities from biogas than CO_2-reductions. This has, however, not been investigated further in this paper.

There are investments in combination technologies in all scenarios, but the usage of the natural gas technologies is relatively low, and the existing combination technologies are not used much. This suggests that gas primarily is used as regulating power. However, with very high CO_2-costs, combination technologies are used as base-load during winter and regulating power during summer. Furthermore, there is an increase in export of electricity in this scenario, which can be explained by the fact that the high CO_2-cost reduces the biomethane cost, and thereby increases biomethane's competitiveness compared to other electricity sources in the surrounding countries.

The scenario with the CO_2-cost estimate by Ref. [40] leads to an extensive usage of biogas that exceeds the potentials described in Ref. [22]. The lack of biogas resources could partly be overcome by biogas upgrading through methanation where hydrogen is used to upgrade the biogas. This could be investigated further in an energy system where the upgrading of biogas is included. This requires new estimates of the biogas CO_2-emissions, since upgraded biogas through methanation contains a lower share of manure per GJ and thereby also another level of CO_2-emissions.

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Nomenclature

Sets

$\mathscr{A}\mathscr{G}\mathscr{K}$	Combination of areas and technologies where capacity exists
$\mathscr{A}(c)$	All areas in country c
$\mathscr{A}$	All areas
$\mathscr{G}^2(g)$	Secondary technologies for primary technology g
$\mathscr{G}^{elec,1}$	Primary technologies producing electricity
$\mathscr{G}^{ext,1}$	Primary technologies that are extraction units
$\mathscr{S}$	All seasons
$\mathscr{T}$	All time periods

Variables

$vge_{a,g,s,t}$	production of electricity in area a, on technology g, season s and time t
$vgf_{a,g,s,t}$	usage of fuel in area a, on existing technology g, season s and time t
$vgfn_{a,g,s,t}$	usage of fuel in area a, on new technology g, season s and time t
$vgh_{a,g,s,t}$	production of heat in area a, on technology g, season s and time t

Parameters

C_g^v	Amount of electricity generation reduction per unit of heat generated on technology g
$GMIN2F_{c,f,f'}$	Common target in country c for fuel type f and f'
$c_{a,g}$	Capacity of technology g in area a
$cost_g$	The cost of producing electricity on technology g
$de_{a,s,t}$	The demand of electricity in area a in season s and time t
$fuel(g)$	Fuel type used on technology g
vge_g^{max}	The maximum electricity production on technology type g
vge_g^{min}	The minimum electricity production on technology type g

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Paper F

Modelling of renewable gas and fuels in future integrated energy systems

Modelling of renewable gas and fuels in future integrated energy systems

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Abstract

The Danish government has set an ambitious target of achieving a fossil fuel independent energy system by 2050. Renewable gas and the gas infrastructure can establish stronger couplings between energy systems, and can potentially play a key role in the future sustainable energy system.

This study investigates the role of renewable gas and fuels in the future Danish energy system. The optimisation model OptiFlow is applied to reflect production of renewable gas and fuel and hard-linked to the energy systems model Balmorel, allowing modelling of the gas and fuel chains from resource collection to end consumers. Co-optimising OptiFlow and Balmorel leads to the socio-economic optimal system, where optimisation of investments and operations is facilitated for the integrated electricity, district heating, and gas system considering also the biofuel demand from the transport sector.

The results show that production of renewable gas and fuels is socio-economically attractive in the investigated scenarios. Renewable gas should be injected into the natural gas pipeline, or be used in biofuel conversion technologies. This study finds methanol as the most socio-econimically attactive biofuel option. The analysis shows that geographical allocation of resources has an impact on the results, which implies that a spatial representation of the resources is necessary when including bioenergy in energy systems modelling.

Keywords:
Integrated energy system modelling, Renewable gas, Renewable fuels, Balmorel model, OptiFlow model

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1. Introduction

The Danish government has announced an ambitious long-term vision of achieving a fossil fuel independent energy system by 2050. To facilitate an effective and cost-efficient green transition, gas as a fuel and the gas infrastructure might play a key role. Given the long-term energy policy targets, declining gas consumption and limited natural gas resources, it is necessary to study the development of the gas system and, in particular, integration of renewable (RE) gas and its production within the energy system.

The main potential benefits for future use of the gas infrastructure and utilisation of RE-gas are: 1) RE-gas can be converted into liquid fuels used in the transportation sector, 2) RE-gas can be produced flexibly from renewable resources or electricity based on variable renewable energy (VRE), 3) the existing natural gas infrastructure can act as a seasonal storage for RE-gas; and 4) RE-gas can be used to generate electricity in peak load situations, to provide process heat for the industrial sector and as a transport fuel [1, 2, 3, 4, 5, 6, 7]. Therefore, RE-gas can potentially play a prominent role in the future Danish energy system, which has high shares of variable renewable energy and a decarbonised transportation sector.

Gas is a key energy carrier in the Danish energy system, accounting for nearly 17% of the total energy consumption in 2015 [8]. Current Danish gas demand is primarily supplied by the large natural gas reserves in the North Sea, making Denmark self-sufficient with natural gas. In addition, local biogas is becoming economically attractive for both local use and grid injection, the latter accounting for approximately 2.5% of the Danish gas consumption in the first half-year of 2016 [9], and it is expected to increase drastically in 2017, see [10]. The increasing trends of locally distributed renewable gas (RE-gas) production technologies entering the gas market add an interesting new dimension to the Danish gas supply.

The role of bioenergy, such as renewable gas and fuels, in the energy system has been investigated in a number of papers. In [11], it is shown that bioenergy can meet the residual demand in 2050 after removing the demand that can be satisfied by non-bioenergy renewable energy options and energy efficiency options. In [12], the usage of bioenergy in the UK energy mix in 2050 is considered using the energy systems model MARKAL. It shows that bioenergy is used in the electricity and heat sector, and included in the transportation sector when targets for a reduction in carbon emissions are high. Börjesson et al. [13] have, by applying the MARKAL model, looked into the possible usage of biomass in the electricity, heat, and transportation sector in Sweden and how the usage and price is affected by goals for CO_2 reductions and phasing out of fossil fuels in the transportation sector. The conclusion is that the total bioenergy utilisation increases, even though the biomass prices also do it. In [14], the competitiveness of bioenergy in the heating sector compared to the transportation sector is evaluated using the EnergyPLAN model. It is found that due to a low price on electricity that can be used in heat pumps, the usage of bioenergy in the transportation sector makes most sense. In [15], how to use the bioenergy in the Norwegian heat sector is being evaluated using the TIMES model. However, to our knowledge few papers have addressed in detail the conversion of biomass to other fuels and its integration in energy systems models. The sustainable transition of the Danish energy system has previously been studied using integrated energy assessment tools, e.g. in [16, 17, 18]. To our knowledge, only four of these studies have addressed future energy systems scenarios with detailed focus on the gas system, see [19, 20, 1, 2].

Conversion of biomass to bioenergy is in most of the literature extensively represented using supply chain models, see e.g. the literature reviews in [21, 22, 23]. As identified in [22], several papers are about regional supply chain modelling, but in most of them the focus is on one specific end-product and not on a variety of options such as transport fuels or gas for co-generation. In the papers [24, 25, 26, 27], the optimal end-products are found by including decisions on which technologies to invest in. The final end-products depend on their market prices and does not reflect the optimal usage of resources in a wider perspective than what is best for the supply chain; neither the impact that a large utilisation of biomass might have on the markets, which might not be marginal. This means the optimal decision for the full energy system is left out and only the optimal solution for the supply chain owner is found.

This article investigates the role of renewable gas production (biogas, synthetic natural gas (SNG), biomethane, and hydrogen), as well as renewable liquid fuel production (methanol, dimethyl ether (DME), biodiesel, and ethanol) in a future renewable based Danish energy system. As the Danish energy system will undergo a radical transformation towards stronger sector integration [6, 28], a holistic system perspective is needed to assess the optimal future socio-economic value of RE-gas utilisation. This study models the production of RE-gas and RE-fuels by linking the energy systems model Balmorel [29], to the spatio-temporal network-flow model OptiFlow [30], in which the production of RE-gas has been defined. This framework enables detailed modelling of the gas chain from up-stream renewable gas production to end consumers or other conversion technologies. Furthermore, it accounts for the spatial and temporal system integration between gas, electricity, and district heating systems.

2. Method

An energy systems model must be selected to evaluate the role and impacts of renewable gas and fuel production. An overview of existing energy systems models can be found in [31]. Due to the detailed spatial resolution, required to represent biomass availability and district heating networks, and to the need of having representative temporal profiles, the energy systems model Balmorel has been chosen. In addition, Balmorel is an open-source model, which enables the possibility to develop and integrate new optimisation features.

2.1. Balmorel

Balmorel is an open-source energy system optimisation model, which currently includes the electricity and combined heat and power sectors. The model relies on a bottom-up modelling approach and is a deterministic, partial equilibrium model, which assumes perfect competition. The Balmorel model entails a comprehensive representation of technical components in the current energy system, e.g. electricity and heat generation technologies and power transmission lines. Balmorel computes the conversion of primary energy to electricity and district heating, the storage of heating and the transmission of power through

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interconnections. The Balmorel model allows simultaneous optimisation of both investments and operational decisions for dispatch [29].

The objective of Balmorel is to maximise social welfare, which is equivalent to minimise the total cost of the system when assuming inelastic energy demands. Balmorel can be run in several modes, e.g. economic dispatch, unit commitment, myopic or perfect foresight approach between and within years, etc. In this paper, Balmorel is run using economic dispatch with investments, and minimising the total costs for satisfying the district heating and power demands, using a perfect foresight approach within the year of optimisation. A simplified version of the main equations used in Balmorel for electricity and district heating generation are described below. The nomenclature is found in Appendix A.

Minimize

$$z = \sum_{a\in\mathcal{A}}\sum_{g\in\mathcal{G}}\sum_{s\in\mathcal{S}}\sum_{t\in\mathcal{T}} c_g^{vOP}\cdot p_{a,g,s,t} + \sum_{a\in\mathcal{A}}\sum_{g\in\mathcal{G}}(c_g^{fxOP}+c_g^{CAP})p_{a,g}^{max} + \sum_{r,r'\in\mathcal{R}^{ex}(r)} c_{r,r'}^{CAP}\cdot p_{r,r'}^{trans} \tag{1}$$

Subject to

$$p_{a,g,s,t} \leq p_{a,g}^{max} \qquad \forall\ a\in\mathcal{A}, g\in\mathcal{G}, s\in\mathcal{S}, t\in\mathcal{T} \tag{2}$$

$$p_{r,r',s,t}^{trans} \leq p_{r,r'}^{trans} \qquad \forall\ r\in\mathcal{R}, r'\in\mathcal{R}^{ex}(r), s\in\mathcal{S}, t\in\mathcal{T} \tag{3}$$

$$\sum_{a\in\mathcal{A}(r)}\sum_{g\in\mathcal{G}} p_{a,g,s,t}^{el} + \sum_{r'\in\mathcal{R}^{im}(r)} e_{r',r}\cdot p_{r',r,s,t}^{trans} - \sum_{r'\in\mathcal{R}^{ex}(r)} p_{r,r',s,t}^{trans} = d_{r,s,t}^{el} \quad \forall\ r\in\mathcal{R}, s\in\mathcal{S}, t\in\mathcal{T} \tag{4}$$

$$\sum_{g\in\mathcal{G}} p_{a,g,s,t}^{dh} = d_{a,s,t}^{dh} \qquad \forall\ a\in\mathcal{A}, s\in\mathcal{S}, t\in\mathcal{T} \tag{5}$$

$$p_{a,g,s,t} \geq 0 \qquad \forall\ a\in\mathcal{A}, g\in\mathcal{G}, s\in\mathcal{S}, t\in\mathcal{T} \tag{6}$$

$$p_{r,r',s,t}^{trans} \geq 0 \qquad \forall\ r\in\mathcal{R}, r'\in\mathcal{R}^{ex}(r), s\in\mathcal{S}, t\in\mathcal{T} \tag{7}$$

$$p_{a,g}^{max} \geq 0 \qquad \forall\ a\in\mathcal{A}, g\in\mathcal{G} \tag{8}$$

$$p_{r,r'}^{trans} \geq 0 \qquad \forall\ r\in\mathcal{R}, r'\in\mathcal{R}^{ex}(r) \tag{9}$$

Equation 1 represents the objective function, and as a result of the optimization, the total cost for satisfying the electricity and district heating demand, z, is minimized. The variable costs of operation of the technology g, including costs related to fuel consumption and environmental taxes, are given by c_g^{vOP}; and the amount of commodity associated to those costs, produced or consumed by a specific technology g, located in the area a, at each time period, defined by the temporal slice s, t, is given by $p_{a,g,s,t}$. The annualised capital expenditures in technology g are defined in c_g^{CAP}, which takes into account the discount rate and the economical lifetime of the investments, which are defined by the variable $p_{a,g}^{max}$, which represents the capacity installed of technology g in area a

Equation 2 represents the constraint of flow of a commodity, $p_{a,g,s,t}$, at each time period s, t, given by the installed capacity of technology g in the area a. Similarly, Equation 3

4

describes the limits to power transmission between interconnected regions r, r' given by the capacity of the lines.

Equation 4 ensures that the electricity demand, $d^{el}_{r,s,t}$, is met in all regions (geographical areas a are aggregated into transmission regions r) and time periods. Electricity might be transmitted between regions, where the variable $p^{trans}_{r,r',s,t}$ shows the amount of electricity exported from region $r \in \mathcal{R}$ to region $r' \in \mathcal{R}^{exp}(r)$, and the variable $p^{trans}_{r',r,s,t}$ denotes the amount of electricity imported, including losses, from the region $r' \in \mathcal{R}^{imp}(r)$ towards r during the time period s, t. Similarly, Equation 5 represents that all the district heating demand, $d^{dh}_{a,s,t}$, is satisfied in all areas and time periods, but without the possibility of heating exchange between areas. Equations 6–9 ensure that all the variables, excepting the total costs of the system z, are non-negative.

Availability of resources, including fluctuation of variable energy; such as wind, solar or hydropower; water storage in hydro reservoirs or heat storage, as well as operational restrictions, e.g. related to operation of combined heat and power plants, are not described in the equations above; however, they are all constraints of the optimisation in Balmorel.

Renewable gas is currently included to a limited extent in Balmorel, and the usage of biomass for energy conversion is only modelled for combustion processes. This means that the production of e.g. biogas and bio-SNG is not directly included in the model, but is represented by a fuel price in Balmorel, equivalent to their production cost or their market value, see e.g. [32]. To allow a better representation of renewable gas in the integrated Danish energy system, the spatio-temporal network optimisation model, OptiFlow, is hard-linked to Balmorel.

2.2. OptiFlow

OptiFlow is a generalised, spatio-temporal network optimisation model, which may represent any network flow related to e.g. energy, mass, economy or environment. It is a deterministic partial equilibrium model built upon a bottom-up approach, as Balmorel, which facilitates their integration. OptiFlow is an open-source tool that allows modelling of networks with high spatial and temporal resolution, which in particular is important in systems with high shares of generation from variable renewable energy sources and locally distributed production and consumption, such as Denmark.

OptiFlow can perform optimisation based on a multi-criteria approach for any selected flow of the network, following the principle of Pareto efficient frontier; however, in this study, the model is hard-linked with Balmorel; therefore, both objective functions are integrated to minimize the total system costs. OptiFlow optimises the transportation of resources and products, as well as investments and operations of different technologies for their transformation and storage, subjected to defined boundary conditions, such as the surrounding energy system. OptiFlow allows optimising the location, size and operation of conversion plants, depending on e.g. costs of transporting local biomass resources, their seasonal availability and the existence of district heating demand.

The model is formulated as a generalised network model, based on node-arc relationships. The applied terminology applies Processes (P) as the nodes, connected through Flows (F) as the arcs, with Processes classified into Source (P^{So}), Sink (P^{Si}), Buffer (P^B), Interior

(P^I), Transport (P^T) and Storage (P^{St}) Processes. The topology of the connections between nodes and arcs is described through the set $R^{APPF}_{a,p,p',f}$, which defines that a Flow f goes from the Process p to the Process p' in the Area a.

The Buffer Processes represent the relationship with the background system or the boundary conditions. In a Buffer Process Flows can enter and/or leave, e.g. consumption or production of a resource, emissions or capture of CO_2, expenditure or earnings, etc. The sign of the Buffer Process net flow, $V^B_{a,p,f,s,t}$, can be positive, negative or zero, as expressed in Equation 10.

$$V^B_{a,p,f,s,t} = \sum_{\substack{p' \in \mathcal{P} \\ |(a,p,p',f) \in \mathcal{R}^{APPF}_{a,p,p',f}}} V_{a,p,p',f,s,t} - \sum_{\substack{p'' \in \mathcal{P} \\ |(a,p'',p,f) \in \mathcal{R}^{APPF}_{a,p'',p,f}}} V_{a,p'',p,f,s,t}$$
$$\forall a \in \mathcal{A}, p \in \mathcal{P}^{\mathcal{B}}, f \in \mathcal{F}, s \in \mathcal{S}, t \in \mathcal{T} \tag{10}$$

Buffer Processes might represent relationships outside the boundary conditions, such as production or consumption of a resource at a specific market price, greenhouse gas emissions or monetary exchanges. In addition, the net Buffer flow, $V^B_{a,p,f,s,t}$, might also be linked, through soft or hard-linkages, to other models, as the energy tool Balmorel. Source Processes are Buffer Processes that only have Flows entering the network, such as, resources, feedstocks, etc. In contrast, Sink Processes are Buffer Processes that only have Flows leaving the system, such as waste, products that are sold to the market, etc. By applying this modelling framework, the direction of the Flow from Source Processes and to Sink Processes are known beforehand, unlike the net Flow from Buffer Processes, whose sign is unknown.

OptiFlow allows multiple Flows to enter and/or leave Interior Processes, where they can be transformed to other Flow or Flows, mixed into one Flow or split in several Flows with the same or different characteristics than the inlet Flow. Flows can either enter or leave a specific Process with fixed or variable ratios. A simplified mathematical formulation for the conversions in Interior Processes is expressed in Equation 11, where the parameter $c^{APFF}_{a,p,f,f'}$ describes the relationships of transformation, splitting or joining of a Flow f into a Flow f' in the Process p in the Area a.

$$\sum_{\substack{p' \in \mathcal{P} \\ |(a,p',p,f) \in \mathcal{R}^{APPF}_{a,p',p,f} \\ \wedge (a,p,f,f') \notin R^{1many}_{a,p,f,f'}}} V_{a,p',p,f,s,t} \cdot c^{APFF}_{a,p,f,f'} + \sum_{\substack{p' \in \mathcal{P} \\ |(a,p',p,f) \in \mathcal{R}^{APPF}_{a,p',p,f} \\ \wedge (a,p,f,f') \in R^{1many}_{a,p,f,f'}}} V_{a,p',p,f,s,t}$$
$$= \sum_{\substack{p'' \in \mathcal{P} \\ |(a,p,p'',f') \in \mathcal{R}^{APPF}_{a,p,p'',f'} \\ \wedge (a,p,f,f') \notin R^{1many}_{a,p,f,f'}}} V_{a,p,p'',f',s,t} + \sum_{\substack{p'' \in \mathcal{P} \\ |(a,p,p'',f') \in \mathcal{R}^{APPF}_{a,p,p'',f'} \\ \wedge (a,p,f,f') \in R^{1many}_{a,p,f,f'}}} V_{a,p,p'',f',s,t} \cdot c^{APFF}_{a,p,f,f'}$$
$$\forall a \in \mathcal{A}, p \in \mathcal{P}, f \in \mathcal{F}, f' \in \mathcal{F}, s \in \mathcal{S}, t \in \mathcal{T} \tag{11}$$

On the left side of the equation there are the Flow or Flows f entering the Process p from the Process or Processes p', and on the right side there are the Flow or Flows f' leaving the Process p towards the Process or Processes p''. The parameter $c^{APFF}_{a,p,f,f'}$ multiplies the input Flow, i.e. f, to get the Flow f' through transformation and/or combination of one or more Flows f in the Process p; however, when a Flow f is split into several Flows f' in the Process p, which is defined in the set $R^{1many}_{a,p,f,f'}$,the parameter $c^{APFF}_{a,p,f,f'}$ multiplies the output Flow f'.

OptiFlow enables transportation of resources across connected geographical areas by different transportation means. As high transportation costs per unit of energy is associated to transport of low-energy density and high water-content resources, such as manure; this feature is key when modelling renewable gas production systems. Specific Flows f can be transported from an Area a to another Area a' by means of different transportation types defined as transport Processes P^T, e.g. trucks, which is described through the set $R^{AAPF}_{a,a',p,f}$. The equation for the transportation process is presented in Equation 12.

$$V_{a,p',p,f,s,t} + \sum_{\substack{a' \in \mathcal{A} \\ |(a',a,p,f) \in \mathcal{R}^{AAPF}_{a',a,p,f}}} V^{transport}_{a',a,p,f,s,t} = V_{a,p,p'',f,s,t} + \sum_{\substack{a' \in \mathcal{A} \\ |(a,a',p,f) \in \mathcal{R}^{AAPF}_{a,a',p,f}}} V^{transport}_{a,a',p,f,s,t}$$
$$\forall \{a \in \mathcal{A}, p \in \mathcal{P}^{\mathcal{T}}, p' \in \mathcal{P}, p'' \in \mathcal{P}, f \in \mathcal{F} | (a,p',p,f) \in \mathcal{R}^{APPF}_{a,p',p,f} \wedge (a,p,p'',f) \in \mathcal{R}^{APPF}_{a,p,p'',f}\},$$
$$s \in \mathcal{S}, t \in \mathcal{T} \tag{12}$$

Moreover, OptiFlow allows intra-seasonal and inter-seasonal storage processes and enables unique flows to be modelled, so that the specific properties of the flows, such as energy content, water content, nutrient content, etc., can be tracked throughout the network.

Based on the above model description, OptiFlow allows flexible modelling of complex networks with a detailed temporal and spatial resolution, including transport. Therefore, it is a suitable tool for optimising the complete chain representing renewable gas and fuel production and their integration in future energy systems.

2.3. Modelling of renewable gasses and fuels in OptiFlow

In this study, OptiFlow is used to model the energy chain from renewable energy resources, transportation systems, technology processes, the RE-gas flows to the final consumption or to other conversion technologies producing liquid fuels or electricity and heat. The modelled network is shown in Figure 1.

OptiFlow models renewable gasses and fuels as an integrated part of the energy system, facilitated by a detailed spatial and temporal resolution. The modelling framework includes endogenous optimisation of, for example, investment decisions, transport of resources, and operation of production technologies and storage facilities.

In the analysis, different plant types are allowed to be installed in specific areas. Biogas production from anaerobic digestions is installed in smaller and medium size rural areas. Small scale air-blown thermal gasification plants producing syngas, which can be used in gas engines for electricity and heat generation are located in smaller and medium size areas. Large scale thermal gasification plants, e.g. circulating fluidised bed (CFB) gasifiers or thermal gasification plants which use oxygen as a gasification agent, for bio-SNG production,

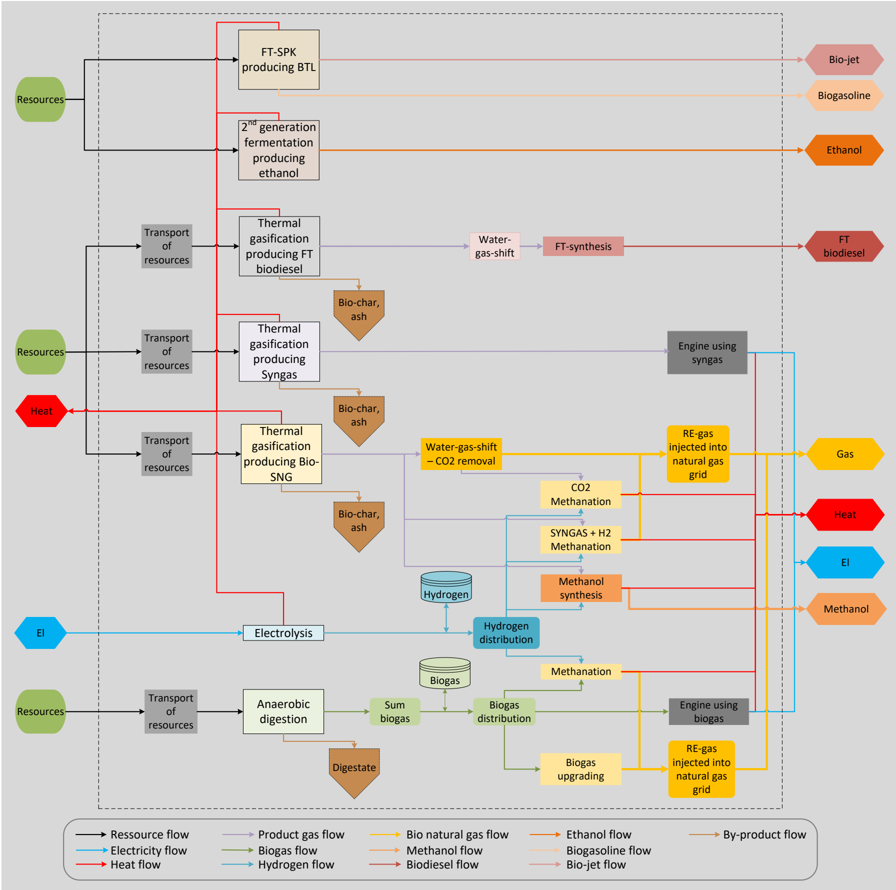

Figure 1: The network implemented in OptiFlow

i.e. with natural gas quality, as well as methanol production, are geographically placed in central areas, which have access to larger district heating networks. Large scale gasifiers in combination with Fisher-Tropsch (FT) synthesis for producing biodiesel and other hydrocarbons with varying carbon chains, such as kerosene and benzene are installed in large district heating networks.

2.4. Linkage of OptiFlow and Balmorel

OptiFlow can be operated as a stand-alone model; however, in this study, OptiFlow is co-simulated with Balmorel to represent the couplings between the renewable gas and fuel production, and the energy system. Figure 2 illustrates a simplification of the modelling

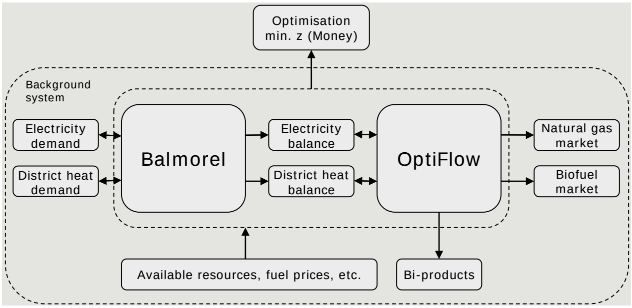

Figure 2: Co-simulation of OptiFlow and Balmorel

framework implemented in OptiFlow and the interplay with Balmorel. By hard-linking OptiFlow and Balmorel simultaneous exchanges of metrics between both models appear through some selected Buffer Variables in OptiFlow:

1. Exchange of monetary flows through the objective function, by adding the term $V^B_{a,p,f,s,t}$ for $f = Money$, i.e. the net flow in OptiFlow of money, to the right side of the Equation 1.
2. Electricity and district heating generation and consumption are linked to the electricity and heat balancing equations in Balmorel, adding the terms $V^B_{a,p,f,s,t}$ for $f = Electricity$, and $V^B_{a,p,f,s,t}$ for $f = District\ Heating$, i.e. the net flows of electricity and district heating generation, to the left side of Equations 4 and 5, respectively.

In addition to the hard-linking of the models, both OptiFlow and Balmorel interact with the background system with respect to, e.g. fuel consumption, using the same common exogenous variables. Furthermore, OptiFlow interacts with the background system when RE-gas is injected to the transmission grid, and with the production of biofuels, which are produced on-demand. In case the simultaneous optimisation of Balmorel and OptiFlow finds the energy conversion economically feasible, it will sell the energy carrier to the market, subjected to constraints in resource consumption given by their geographical and seasonal availability.

3. Renewable gas and fuel technologies

This study describes and evaluates the role that different technologies might play in the conversion and use of RE-gas, including anaerobic digestion, thermal gasification, electrolysis, storage facilities, gas upgrading, methanation, Fischer-Tropsch syntheses and methanol syntheses.

3.1. Biogas from anaerobic digestion

In this study, the anaerobic digestion can use two types of feedstocks, straw and a mixture of manure and wet biomass. The biogas produced is assumed to have a methane content of 65% and it can be upgraded to biomethane by removal of CO_2 or catalytic methanation of CO_2. Digestate is an anaerobic digestion process by-product, but it is considered to have no monetary nor nutrient value.

Due to the high transportation costs and the low energy content of the resources used for anaerobic digestion, biogas is produced and upgraded locally in areas where resources are available, which is mainly in rural areas.

3.2. Thermal gasification

In this study, thermal gasification plants can use four resources: wood, straw, wood pellets and refuse derived fuel (RDF). The composition of the output gas from the gasifier i.e. product gas depends on several parameters, such as, type of gasification process, properties of feed-stock, temperature and pressure levels in the gasification process, as well as gasification agent.

To enable modelling of thermal gasification technologies in a comprehensive energy systems modeling framework, such as co-simulation of Balmorel with OptiFlow, the following assumptions with respect to the type of thermal gasification plants, as well as location, have been made.

Utilisation of the output gas might require certain specifications or compositions of the output gas. By selecting a suitable design of the thermal gasification plant, the specifications for the composition of the gas can be adapted. To further achieve the specifications, removal or conversion of components like particulates, alkali compounds, tars, sulphur, and nitrogen compounds, might be needed (see Figure 1). In this study, the main product gas characteristics is specified based on the ratio of hydrogen to carbon monoxide, which is considered as a simple though reliable measure.

In general, product gas, which also contains nitrogen components can, after being cleaned, be used in cogeneration gas engines. Therefore, an air-blown gasifier type is sufficient for that purpose.

The stoichiometry of a synthesis reaction might require a certain composition of a nitrogen-free product gas. Hence, in the chain where a gasification process is followed by a synthesis process, an oxygen-blown gasifiers or a CFB gasifier, must be used. In this study, bio-SNG from thermal gasification can be produced applying the three following approaches: 1) methane can be produced by using water-gas-shift reaction and CO_2 removal techniques, 2) methane synthesis, where H_2 is mixed with the product gas in order to achieve the optimal relation between carbon and hydrogen, 3) using removed CO_2 and hydrogen in a catalytic methanation synthesis. In addition to the bio-SNG production, methanol, biodiesel and bio-jet fuel is produced using methanol synthesis and FT-synthesis, respectively, see Figure 1.

The combination of thermal gasification plants and synthesis process can benefit economy-of-scale as well as begin located in areas with large district heating demands, allowing revenues from excess heat. Thus, these plants are assumed to be located in large central district heating areas.

3.3. Electrolyses

Hydrogen can be produced by electrolysis using electricity and water as inputs. Flexible production of hydrogen can potentially play a key role in the future Danish energy system. However, in this study, the dimension of the electrolyzer is designed to satisfy the demands of hydrogen needed to ensure a satisfactory stoichiometric ratio for the synthesis reactions aforementioned.

3.4. Energy and mass balances

Ensuring that energy and mass balances holds is key in the modelling of renewable gas and fuel production. This section presents the main theoretical methodology used to calculate proportions of inflows for a given energy conversion. Moreover, the calculated rations required for the methane and methanol synthesis are implemented in the OptiFlow modelling framework.

3.4.1. Synthesis of methane

Hydrogenation of carbon mono- and di-oxide is described by the following chemical reactions. For production of methane using hydrogenation of carbon dioxide, the carbon dioxide reacts with hydrogen:

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O + \Delta H, \Delta H = -164.9kJ/mol \tag{13}$$

Hydrogenation of carbon mono-oxide to methane consists of the two following reactions. Carbon mono-oxide can be produced using a reverse water-gas shift reaction, where carbon dioxide reacts with hydrogen:

$$CO_2 + H_2 + \Delta H \longrightarrow CO + H_2O+, \Delta H = +41.5kJ/mol \tag{14}$$

Hydrogenation of carbon mono-oxide to methane is expressed by the Sabatier reaction, carbon monooxide CO reacts with hydrogen to form methane:

$$CO + 3H_2 \longrightarrow CH_4 + H_2O + \Delta H, \Delta H = -206kJ/mol \tag{15}$$

3.4.2. Synthesis of methanol

Hydrogenation of carbon mono- and di-oxide to methanol can be expressed by the following reactions:

$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O + \Delta H, \Delta H = -40.9kJ/mol \tag{16}$$

$$CO + 2H_2 \longrightarrow CH_3OH + \Delta H, \Delta H = -90.7kJ/mol \tag{17}$$

3.4.3. Energy and mass balances for methane synthesis assumed in this study

To produce bio-SNG using thermal gasification, a water-gas shift reactor or hydrogen injection is needed to obtain a hydrogen to carbon mono-oxide ratio at 3, which is the optimal methanation stoichiometry. For methane synthesis, where product gas and hydrogen is mixed to obtain the optimal methanation stoichiometry, the energy balance yields that 44% cleaned syngas and 56% hydrogen is mixed in the methane synthesis. With other words, almost a double amount of bio-SNG can be produced when using the methane synthesis technology.

For biogas, the energy balance shows that the ratio has to be 61% cleaned biogas and 39% hydrogen. In this way, by using the methanation technology on biogas, 1.5 times more biomethane can be produced than by removal of CO_2 with a scrubbing technology.

3.4.4. Energy and mass balance for methanol synthesis assumed in this study

The highest efficiency of the methanol synthesis is achieved when operating with an M ratio at 2.05 [33]. The M ratio expressed by the following equation:

$$M = \frac{H_2 - CO_2}{CO + CO_2} \tag{18}$$

The composition of the product gas obtained from the thermal gasification process yields a hydrogen to carbon mono-oxide ratio of the raw syngas at 1.27 [33]. By hydrogen injection, the hydrogen level is raises. The calculations shows that ratio between cleaned product gas and hydrogen is 2.22. In other words, the energy input to methanol synthesis unit has to be: 69% cleaned syngas and 31% hydrogen.

4. Data assumptions

In this study, the simultaneous optimisation of OptiFlow and Balmorel leads to the socio-economic optimal system, given specified demands, fuel potentials, and fuel prices. We use a simplification of socio-economy, meaning that we consider only the CO_2 abatement cost and exclude all other externalities from the optimisation.

4.1. Spatial and temporal resolution

The energy systems optimization includes data for the Nordic countries and Germany, with a focus on Denmark, e.g. the Danish district heating system is represented using 35 demand district heating areas, while only few district heating areas are modelled in the surrounding countries.

This study looks into the snapshot of one year, 2050, to assess how the future energy system might look like and which role RE-gas production might play. 2050 is modelled using four representative weeks and assuming a perfect foresight approach within that year.

Input type	Fuel potential
Manure, wet biomass	67 PJ
Straw	148 PJ
Refuse derived fuel (RDF)	5 PJ
Wood	40 PJ
Wood Pellets	import of 28 PJ is allowed

Table 1: Fuel potentials in Denmark by 2050

4.2. Resources

The national available resources are taken from [4] and are listed in Table 1. The national resources are implemented in OptiFlow according to the geographic area a for the harvesting of resources, e.g. manure and wetbio resources are spatially allocated in the 35 areas in OptiFlow based on [34]. The potential production of biomethane in Denmark using manure, straw and waste can be seen in figure 3. Moreover, the modelling framework allow import of wood pellets, i.e. 28 PJ. These resources are, however, allocated equally between the six largest district heating networks, where large scale thermal gasification plants with downstream synthesis processes can be installed.

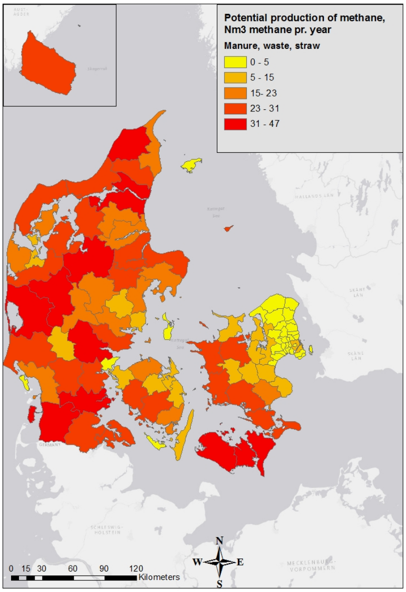

Figure 3: The potential production of biomethane in Denmark

4.3. Fuel prices and CO_2-cost

Fuel prices and the CO_2-cost are adopted from the Carbon-Neutral Scenario in the Nordic Energy Technology Perspective (NETP) [35], which corresponds to the 2°C scenario in the Energy Technology Perspective (ETP) conducted by IEA [36]. The prices represent a sustainable future dominated by renewable based energy production. The green energy transition is motivated by the high CO_2-costs, representing the marginal abatement cost. In this future system, the demand for fossil-fuels is low, resulting in low fossil-fuel prices. The fuel prices used in this study are shown in Table 2. The CO_2-cost used is 135.8 €/ton CO_2 [35].

Fuel	Price
Natural Gas	6.98
Coal	2.35
Fueloil	11.67
Gas oil	14.25
Oil	16.40
Straw	8.92
Wood chips	9.91
Wood pellets	11.71
Nuclear, uranium	1.94

Table 2: Fuel prices, all in €/GJ

4.4. Techno-economic data for renewable gas and fuel production technologies

The techno-economic data for RE-gas production technologies are taken from [37, 38, 39] and is presented in Table 3. The lifetime of the biogas upgrading technology is assumed to be 15 years, while the lifetime of the other technologies is estimated to be 20 years.

4.5. Energy demands

The electricity and district heating demands by 2050 are extracted from the NETP [35]. In this scenario, the classical electricity demand is 170 PJ, and electricity for district heating purposes constitute 25 PJ. The demand for heat supplied by the district heating network is 110 PJ. The electricity demands are specified according to the electricity regions, while district heating demands are distributed based on the areas.

To quantify demands for liquid fuels used in the transportation sector, a literature overview is conducted for Danish transportation scenarios by 2050. This overview furthermore highlights promising pathways demonstrated in previous studies. The overview includes Danish studies [4, 40, 41, 42, 43, 44], where more scenarios might be assessed within each study. The results from the studies are obtained primarily using simulation models [4, 40, 41, 42, 43, 44]. Furthermore, some studies do not include methanol or DME [4, 40, 44], making it necessary to use for example biodiesel. Based on the literature review, this study investigated a scenarios with varying utilisation of liquid fuels for transportation, that is, 50 PJ, 100 PJ, and 125 PJ (100PJ + 25PJ for air transportation i.e. biojet fuel).

	Investment costs, [M€/GJ/h]	O&M costs, [k€/GJ/h]	Fuel efficiency, [%]	Output heat, [%]
AD	0.401	-	40%	-
AD mix fuel	0.434	-	47.5%	-
Biogas upgrading	0.117	2.9	100%	-
TG - SYNGAS	0.281	5.5	85%	5%
TG Bio-SNG	0.411	11.2	70%	20%
TG - to synthesis	0.174	7.0	75%	15%
2.gen. Biodiesel plant	0.522	14.7	55%	35%
2.gen. Ethanol plant	0.319	23.0	41%	25%
Biojet plant	0.811	23.0	24% biojet 24% biogasoline	21%
Electrolyzers	0.099	3.0	79%	-
Methanol synthesis	0.049	1.5	115% compared to syngas input	-
Catalytic methanation of CO_2	0.137	6.8	200% compared to syngas input 150% compared to biogas input	17%

Table 3: Techno-economic parameters for RE-gas production technologies. AD: Anaerobic digestion; TG: Thermal gasification

5. Scenarios

A base scenario is conducted with the input parameters presented. However, five sensitivity scenarios are conducted to investigate effects on the renewable gas and fuel production by varying the demands for liquefied fuels, the CO_2-cost, the gas price, and the investment possibility in inter-connectors to adjacent electricity markets.

A summary of how the scenarios differ can be seen in table 4.

Scenario	Investment in transmission	CO_2-cost on top of gas price	Gas price	Biofuel demand
Base	Yes	Yes	6.31 €/GJ	50 PJ
Fuel100	Yes	Yes	6.31 €/GJ	100 PJ
Fuel100+25	Yes	Yes	6.31 €/GJ	100+25 PJ
NoCO2cost	Yes	No	6.31 €/GJ	50 PJ
HighGas	Yes	Yes	12.62 €/GJ	50 PJ
NoTrans	No	Yes	6.31 €/GJ	50 PJ

Table 4: The scenarios and their differences

6. Results

This section presents the scenario results obtained by co-simulating OptiFlow and Balmorel. RE-gas production is strongly coupled with the electricity and district heating sectors. Gas can therefore serve as an energy carrier that will strength the couplings between energy vectors in future energy systems. Therefore, RE-gas productions are assessed using a holistic energy system perspective.

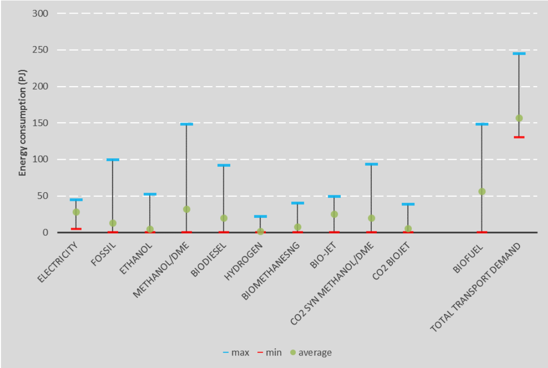

Figure 4: Fuel used in the Danish transportation sector. Based on studies included in the literature overview.

6.1. Electricity and district heating systems

The simulation year in this study is 2050. It is an underlying assumption that no existing generation capacity is installed in the system, meaning that the energy system is built up based on technology costs in 2050. With the high marginal CO_2 abatement cost in 2050, this leads to a renewable-based energy system. By 2050, the integrated Nordic and German electricity system is dominated by variable renewable energy (VRE) sources, with 47% wind and 12% solar PV. The well-functioning Nordic electricity market enables the 26% Nordic hydro power to be efficiently used for balancing variations in electricity production. The remaining 14% of the electricity generation mix is covered by thermal capacity fuelled with biomass.

Figure 5 presents the configuration of the Danish electricity and district heating production by 2050. The figure illustrates a scenario, where the Danish electricity generation portfolio is dominated by VRE sources, where wind constitute 77% and solar PV accounts for 23% of the Danish electricity generation. The district heating sector is to a large extent electrified, however, national waste resources are used as well as excess heat from, for example, biorefineries.

In this future scenario, with high penetrations of VRE generation, electricity prices tend to be volatile. The average electricity price found in the scenarios is approximately 47 €/MWh, with 1 €/MWh difference between West- and East of Denmark. Volatile electricity prices provide the incentive for flexible power-to-gas technologies to produce hydrogen in time periods with low electricity prices.

6.2. Renewable gas and fuel production in Denmark by 2050

The results related to renewable gas and fuel production obtained by co-optimising OptiFlow and Balmorel are presented in Figure 6.

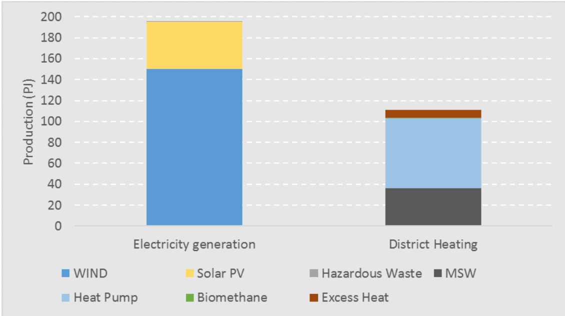

Figure 5: Danish electricity and district heat production by 2050

Figure 6 illustrates that thermal gasification technologies are operated in all scenarios. Furthermore, the results show the general trend of producing biomethane which can be injected into the natural gas pipeline network.

In the Base scenario, the optimisation results in a socio-economically optimal system where biogas is produced and upgraded to biomethane from the mixture of manure and wetbio combined with straw in a co-digestion. Using the co-digestion process is marginally more economically attractive than not adding straw in the process, under the given scenario assumptions. However, biogas production using the mixture of manure and wetbio, i.e. mono-digestion, is operating in areas where the local straw resource is used, illustrating the economic attractiveness of this technology. In this study, the by-product from the anaerobic digestion process do not have an monetary value, however, this could potentially influence the results towards using straw in the anaerobic digestion plant. The results in the base scenario points to the finding that methanol is the most socio-economic attractive biofuel for transportation means, which is in line with previous findings as documented in the literature overview. The methanol is produced downstream to the thermal gasification process, using primarily straw as feedstock, but also the available resource of RDF. Hydrogen is produced to achieve the optimal stoichiometric ratio, yielding a hydrogen production of 20 PJ.

Increasing the biofuel demand to 100 PJ evidently leads to higher resource utilisation. In this scenario, all feed-stock opportunities for thermal gasification plants are used. Local resources are used first, hereafter follow options where resources are transported between areas. Under the given assumptions, wood pellets have importing points at six large district heating areas. In this modelling setup wood pellets are therefore traded at the market price without costs associated to the transportation. The model finds it more economic attractive to utilise wood pellets than transporting local resources over longer distances. However, short distance transportation of straw appear, for example on the island of Fyn—from Nyborg to Odense.

By introducing a demand from the air-transportation sector, the total biofuel demand increases and puts a pressure on the national available resources. As biojet fuel is assumed to

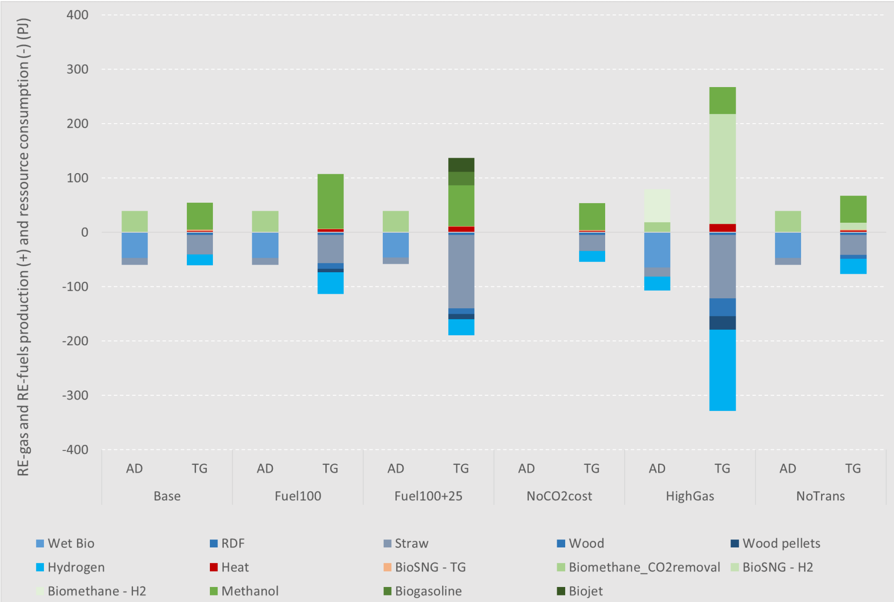

Figure 6: Danish RE-gas and RE-fuels production (+) and fuel consumption (-) by 2050 in the investigated future scenarios. AD: Anaerobic digestion; TG: Thermal Gasification

be produced from straw, the complete national resource of straw is utilised. In this scenario, straw resources are transported to truck between areas across the country. Utilisation of wood and wood pellets obtain levels as in the Fuel100 scenario. As a consequence of the biojet production, biogasoline is produced as a by-product. Hence, biogasoline contribute to the total biofuel production by covering 25 PJ of the demand. Methanol covers the remaining biofuel demand at 75 PJ. The results from this scenario furthermore illustrate the potential benefit of utilising the excess process heat from biorefineries in Denmark.

The NoCO2cost scenario is conducted to elucidate the impact of CO_2-costs on renewable gas production. Evidently, the results show that biogas is not produced in case there are no CO_2-cost on top of the gas price, which was also previously shown in [32]. This furthermore emphasises the need for implementing proper regulatory frameworks to support biogas production.

In the HighGas scenario, the gas price is doubled, which leads to a situation where the system benefits from producing large amounts of renewable gas. In this scenario biomethane is produced both using scrubbing techniques and by methanation of the CO_2 in the biogas. Renewable gas produced from thermal gasification plants with downstream methanation synthesis is also a socio-economic attractive option, producing approximately 200 PJ of

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bioSNG. Hydrogen production plays a key role in this scenario. The results show that hydrogen is produced continuously in most of the simulated time periods, however, hydrogen is not produced in periods with high electricity prices.

In the NoTrans scenario, the model is not allowed to invest in inter-connectors to adjacent electricity markets, leading to an electricity network which is similar to today. By constraining the availability of electricity trade affects the electricity price significantly. As a consequence of this scenario setup, more volatile electricity prices are obtained. Moreover, the annual average electricity price 47 €/MWh which is an increase of 3 €/MWh compared to the base scenario.

To facilitate an efficient integration of increased penetrations of VRE in the future Danish energy system, four sources of flexibility can be used i.e. flexible generation, demand-side flexibility, energy storage facilities, and transmission grid infrastructure. By limiting the availability of electricity transmission, other measures must provide the flexibility needed to balance the electricity system. In this scenario, flexible generation in terms of fast responding co-generation biomethane plants are operated, generating 33 PJ electricity. A total amount of 70 PJ biomethane is utilised of which 40 PJ biomethane is produced in Denmark. Moreover, additional 14 PJ of bio-SNG is produced which can be used in co-generation plants as well. The volatile electricity prices obtained in this scenario creates incentives for increased hydrogen production; hence increases the power-to-gas technology the demand-side flexibility. These results show that by constraining one of the flexibility options, the potential benefit of the remaining flexibility options increases.

7. Conclusions

This study investigated the role of renewable gas production in a future renewable based Danish energy system. As the Danish energy system will undergo a radical transformation towards a system with stronger couplings and interactions between energy vectors in the future, a holistic system perspective is used to assess the future socio-economic value of renewable gas and fuel production. To facilitate the modelling of the production, model developments in the spatio-temporal network optimisation model, OptiFlow, were implemented. Furthermore, OptiFlow was hard-linked to the energy systems model Balmorel, allowing an integrated energy assessment of the production.

This modelling framework allowed a detailed modelling of the gas chain from up-stream renewable gas production, through storage facilities to end consumers or conversion technologies, taking into account the spatial and temporal system integration between the gas, electricity, and district heating system.

The result of the co-optimisation of OptiFlow and Balmorel represents the socio-economic optimal system, where investments and operations optimisation is undertaken for the integrated energy system. The results show that production of renewable gasses and fuels is socio-economically attractive in all the investigated scenarios. Furthermore, the results show that RE-gas directly injected into the natural gas pipeline network is preferred, and that methanol is the preferred RE-fuel.

In the high natural gas price scenarios, the methanation synthesis is used to produce additional methane both after the anaerobic digestion process and the thermal gasification process. In the NoTrans scenario, the availability of the electricity transmission system is limited, which leads to a system where other flexiblility options are utilised, i.e. fast responding biomethane co-generation plants, and improved demand-side flexibility by increased hydrogen production.

The modelling approach applied in this study, allowed the investigation of production with a high temporal and spatial resolution. This was used to show that the deployment of the chosen technologies for producing RE-gas and RE-fuels varies according to the resource allocation, and to show the effect of electricity price on hydrogen production.

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Appendix A. Nomenclature

Sets used in Balmorel and OptiFlow

$\mathcal{A}$	Areas
$\mathcal{S}$	Seasons
$\mathcal{T}$	Time periods in a season

Sets for Balmorel

$\mathcal{A}(r)$	Subset of areas in region $r \in \mathcal{R}$
$\mathcal{G}$	Technologies
$\mathcal{R}$	Regions
$\mathcal{R}^{exp}(r)$	Subset of regions that region $r \in \mathcal{R}$ can export to
$\mathcal{R}^{imp}(r)$	Subset of regions that region $r \in \mathcal{R}$ can import from

Variables for Balmorel

$p^{max}_{a,g}$	Maximum production of technology g in area a
$p^{trans}_{r,r',s,t}$	Transmission of electricity between region r and region r' in the time period s,t
$p^{trans}_{r,r'}$	Power Transmission capacity between Region r and r'
$p_{a,g,s,t}$	Commodity level in area a of technology g in the time period s,t
z	Total cost of the system for satisfying the energy demands

Parameters for Balmorel

c^{CAP}_{g}	Annualised investment cost of technology g
c^{fxOP}_{g}	Fix Operational cost of technology g
c^{vOP}_{g}	Variable operational cost of technology g

Sets for OptiFlow

$\mathcal{R}^{1many}_{a,p,f,f'}$	Flow f that goes inside a process p, where it is transformed into more than one flows f' in the area a
$\mathcal{R}^{AAPF}_{a,a\prime,p^T,f}$	Flow f that can be transported from the area a to the area a'through the transport process p^T
$\mathcal{F}$	Flows
$\mathcal{P}$	Processes
$\mathcal{P}^B$	Subset of buffer processes p
$\mathcal{P}^T$	Subset of transport processes p
$\mathcal{P}^{Si}$	Subset of sink processes p
$\mathcal{P}^{So}$	Subset of source processes p
$\mathcal{R}^{APPF}_{a,p,p',f}$	Topology of flows f from process p to process p' in the area a

Variables for OptiFlow

$V^B_{a,p,f,s,t}$	Net flow f from the Buffer Process p^B in the area a during the time period s,t
$V_{a,p,p'f,s,t}$	Flow f from the Process p to the Process p' in the area a during the time period s,t
$V^{transport}_{a,a\prime,p,f,s,t}$	Flow f that is transported from the area a to the area a' through the transport process p^T during the time period s,t

Parameters for OptiFlow

$c^{APFF}_{a,p,f,f'}$	Relationship between the flow f and the flow f' in the process p in the area a